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AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE 92200 NEUILLY SUR SEINE FRANCE

AGARD ADVISORY REPORT 313

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Mission Planning Systems for Tactical Aircraft (Pre-Flight and In-Flight)

Systèmes de Planification des Missions pour Avions Tactiques (Avant Vol et en Vol)

This report has been prepared at the request of the Avionics Panel and Aerospace Medical Panel of AGARD.

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North Atlantic Treaty Organization
Organisation du Traité de l'Atlantique Nord

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— Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community;

— Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);

— Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;

— Improving the co-operation among member nations in aerospace research and development;

— Exchange of scientific and technical information;

— Providing assistance to member nations for the purpose of increasing their scientific and technical potential;

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Preface

Mission Planning is not new in concept, and as applied to military aircraft missions, it must have been carried out from the very earliest days. Recent events have combined to increase interest in the subject, and the Air Forces of many of the NATO nations are taking steps to develop and procure mission planning systems that have capabilities far in advance of those previously available. In addition, increased interest is being shown in using airborne computer-based systems to plan and re-plan missions while they are in progress.

There are several reasons for this interest, and these include both the technological push resulting from the advances in computers and their peripherals that have recently become available, and the needs of the Air Forces which are changing as their perception of future military scenarios changes. Recent experience from Operation "Desert Storm" is also likely to increase interest in more capable mission planning systems, including those having a mission rehearsal capability.

AGARD Joint-Working Group 15 was established to review mission planning systems and to consider how they are likely to evolve in the future. Its terms of reference specified a programme of two phases and the work carried out in the first of these was previously published as AGARD Advisory Report 296. This report covers the work of Phase Two. The Working Group met five times during Phase Two, and its studies were considerably enhanced by presentations and demonstrations provided by organizations in the host countries. The value of these contributions to the Group's work is gratefully acknowledged. It is hoped that the second report, taken together with the first, will provide a valuable source of information to a wide range of readers in the NATO community.

Préface

La planification de la mission n'est pas un concept nouveau, et en ce qui concerne son application aux missions de l'aviation militaire il a dû être adopté dès les origines. Les événements récents ont amené un renouveau d'intérêt pour ce sujet, et un grand nombre des forces aériennes de l'OTAN prennent des dispositions en vue du développement et de l'acquisition de systèmes de planification de la mission ayant des capacités largement supérieures à ceux qui sont actuellement disponibles. En même temps, un intérêt similaire est manifesté pour des systèmes embarqués gérés par ordinateur pour la planification de la mission et sa replanification en cours de vol.

Cet intérêt s'explique pour diverses raisons et notamment l'essor technologique issu des avancées enregistrées en ce qui concerne les ordinateurs et leurs périphériques, ainsi que les demandes exprimées par les différentes forces aériennes, qui évoluent en fonction de leur appréciation des scénarios militaires futurs. L'expérience acquise récemment lors de l'opération "tempête du désert" suscitera, sans doute, à son tour, un intérêt accru pour des systèmes plus performants de planification de la missions, y compris ceux dotés d'une capacité de répétition de la mission.

Le groupe de travail conjoint No. 15 de l'AGARD a été crée pour évaluer les systèmes de planification de la mission et pour apprécier leur évolution future. Le mandat du groupe définit un programme en deux phases et les travaux de la première phase sont décrits dans le rapport consultatif AGARD No. 296 déjà paru. Le présent rapport couvre les travaux de la phase deux. Le groupe s'est réuni cinq fois, et ses études ont tiré un avantage considérable des démonstrations et des présentations qui ont été organisées par les pays hôtes. Le groupe tient à souligner la valeur de ces contributions pour ses travaux et il espère que ce deuxième rapport, pris ensemble avec le premier, constituera une source d'informations estimable pour un très grand nombre de lecteurs de la communauté de l'OTAN.

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In addition to the contributions of the Working Group members, important and significant inputs were made to the functioning of the Group and to the writing of this report by the following, who acted as alternate members:

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Mr Ian Ross — British Aerospace

Mr Michele Visciola — Alenia DVD

Mr Jacques Krawies — Dassault-Aviation.

During its Phase Two activities, the Working Group was assisted by many individuals, including the staff of AGARD headquarters, whose efforts are greatly appreciated. The Group also thanks Wright-Patterson Air Force Base, British Aerospace, US Naval Medical R&D Command, Sextant Avionique, and the C.S. Draper Laboratory for making available their facilities during the Phase Two activities.

Contents

List of Acronyms

A/A	Air-to-Air
A-S	Air-to-Surface
A/I	Area of Interest
A/N	Alphanumeric
AAFMPS	Advanced Air Force Mission Planning System
ABCCIS	Air Base Command and Control Information System
ACCS	Air Command and Control System
ACO	Airspace Coordination Order
ADRG	ARC Digitized Raster Graphics
AEW	Airborne Early Warning
AFMSS	Air Force Mission Support System
AGARD	Advisory Group for Aerospace Research and Development
AGL	Above Ground Level
AI	Air Interdiction
AI	Arftificial Intelligence
AMP	Aerospace Medical Panel
AMPA	Advanced Mission Planning Aid
AMPS	Airborne Mission Planning System
ATC	Air Traffic Control
ATCCS	Army Tactical Command and Control System
ATF	Advanced Tactical Fighter
ATM	Air Task Message
ATO	Air Task Order
ATOC	Allied Tactical Operations Center
ATP	Allied Tactical Publication
ATPAL	*Air Task Processing at Airbase Level*
AVP	Avionics Panel
AWACS	Airborne Warning and Control System
BAI	Battlefield Air Interdiction
BFA	Battlefield Functional Area
BVR	Beyond Visual Range
C^3	Command, Control and Communications
C^3I	Command, Control, Communications and Intelligence
CAD	Computer Aided Design
CAMPAL	Computer Aided Mission Planning at Airbase Level
CAP	Combat Air Patrol
CAS	Close Air Support
CD	Compact Disk
CE	Copilot Electronique
CINC	Commander in-chief
COC	Combat Operations Center
COMM	Communications
CPS	Cockpit Procedure Simulator
CPU	Central Processor Unit
CRT	Cathode Ray Tube
CVBG/BF	Aircraft Carrier Battle Group/Battle Force
D	Dimension(al)
DARPA	Defense Advanced Research Project Agency
DBA	Database Administrator
DCA	Defensive Counter Air
DFAD	Digital Features Analysis Data
DITAM	Digital Terrain Analysis Model
DLMS	Digital Hand Mass-Storage System
DMA	Defense Mapping Agency
DMI	Direct Manipulation Interface
DTC	Data Transfer Cartridge
DTED	Digital Terrain Elevation Data
DTM	Data Transfer Module
DWIM	Do What I Mean
E&E	Escape and Evasion
ECM	Electronic Counter Measures
EDAM	Enemy Defense Analysis Models
EID	Ecological Interface Design
EO	Electro-optical
ESD	Electronic Systems Division
ESM	Electronic Support Measures
ETA	Expected Time of Arrival
EW	Electronic Warfare
FAC	Forward Air Controller
FAF	French Air Force
FARP	Forward Area Rearm/Refuel Point
FEBA	Forward Edge of the Battle Area
FEZ	Fighter Engagement Zone
FLIR	Forward Looking Infra-Red
FLOT	Forward Line of Own Troops
FWOC	Forward Wing Operations Center
GUI	Graphic User Interface
HCI	Human Computer Interaction
HUD	Head Up Display
IAF	Italian Air Force
IFF	Identification Friend or Foe
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
INTAL	Intelligence at Airbase Level
INTEL	Intelligence
IP	Initial Point
IR	Infra-Red
IRST	Infra Red Search and Track
ISMP	Integrated Strike Mission Planner
IV&V	Independent Validation and Verification
JINTACCS	Joint Interoperability of Tactical Command and Control Systems
JMEM	Joint Munitions Effectiveness Manual
JOG	Joint Operational Graphic
JTIDS	Joint Tactical Information Distribution System
LCD	Liquid Crystal Display
LLTV	Low Light Television
MADAM	Munition and Delivery Analysis Models
MANPRINT	Manpower and Personnel Integration
MARPLES	Military Aircraft Route Planning Expert System

MB	Megabyte
MCS	Maneuver Control System
METAL	Meteo at Airbase Level
MEZ	Missile Engagement Zone
MIDS	Multifunction Information Distribution System
MIL-STD	Military Standard
MISREP	Mission Report
MMA	Mission Management Aid
MP	Mission Planning
MPS	Mission Planning System
MSS	Mission Support System
N/A	Not Applicable
NAFAG	NATO Air Force Armaments Group
NATO	North Atlantic Treaty Organization
NBC	Nuclear Biological Chemical
NLR	National Aerospace Laboratory
NOTAM	Notices to Airmen
OCA	Offensive Counter Air
OPORD	Operations Order
OPS	Operational
OR	Operational Relationship
PA	Pilot's Associate
PC	Personal Computer
PHC	Pilot Hand Controller
PIREPS	Pilot Reports
PPDB	Point Position Database
QRA	Quick Reaction Alert
R&D	Research and Development
RAF	Royal Air Force
RAM	Random Access Memory
RECCE	Reconnaissance
RF	Radio Frequency
RNLA	Royal Netherlands Air Force
ROE	Rules of Engagement
ROM	Read Only Memory
RPV	Remotely Piloted Vehicle
RRDB	Rapidly Reconfigurable Databus
SAM	Surface-to-air missile
SAR	Search and Rescue
SCI	Strategic Computing Initiative
SLAR	Side Ways Looking Airborne Radar
SOC	Sector Operations Center
SORD	Statement of Requirements Document
STANAG	Standard NATO Agreement
TAF	Tactical Air Force
TAMPS	Tactical Aircraft Mission Planning System
TEAMS	Tactical EA-6B Mission Support
TLM	Tactical Line Map
TOT	Time-over-target
TRADOC	Training and Doctrine Command
TV	Television
UAV	Unmanned Air Vehicle
UAV	Unmanned Air Vehicle
UHF	Ultra High Frequency
UIMS	User Interface Management System
USA	US Army
USAF	US Air Force
USN	US Navy
V/STOL	Vertical/Short Take-off and Landing
VFR	Visual Flight Rules
VHF	Very High Frequency
WIMP	Window - Icon - Mouse - Pointer
WVR	Within Visual Range

Chapter 1
Introduction

1.1. BACKGROUND.

AGARD Joint Working Group 15 was authorized in 1988 and commenced work in February 1989. Its terms of reference specified a 3-year period of studies divided into two phases. Phase One was to cover an assessment of the overall concepts of Mission Planning and of the technical possibilities, together with the identification of critical technologies, while Phase Two was to explore in greater detail these critical technologies and their impact upon future mission planning systems. The Working Group decided during Phase One that system tasks and features should be included in their studies, and these then formed an important part of the work of both Phases One and Two.

The results of the Phase One work have been published as AGARD Advisory Report AR-296 (1.1) and this second report presents the work of Phase Two. As the results of the Phase One work are not fully repeated here, it is recommended that the reader of this report should first study AR-296 which provides an essential background. In addition, because of the very limited coverage of in-flight mission planning given in AR-296, additional background and description of current work in this important area is given in Section 1.3 of this report.

In Chapter 8 of AR-296 the Working Group listed the topics which had been identified during Phase One as being potentially worthy of further study in Phase Two. These included both system concepts and system techniques, and comprised

- Distributed Mission Planning Process
- Dynamic Prediction of Battle Evolution
- Interoperability
- Airborne Mission Planning
- Mission Rehearsal
- Data Filtering/Fusion
- Data Protection
- Communication
- Testing / Validation
- Artificial Intelligence
- Computer Graphics
- System Architectures
- Man/ System Design

These topics provided the start-point for the Phase Two work but, as the studies developed, it was found that further refinement was necessary to reflect changed views on the significance of the different topics. As a consequence, the structure of this report corresponds only loosely to the above topics list.

The principal objective of the Phase Two studies was to investigate in detail the above topics and to assess how these would develop in the future and how such developments would impact upon future mission planning systems. An additional task was to recommend any research and development programs which were identified as being important to future improvements in mission planning systems. In carrying out this work the effect of other influences had to be recognized; important amongst these on the technical side is the enhanced performance and the widening role of avionics equipment on board military aircraft, and important in the broader military sense is the new international scenario and its effect upon the missions likely to be carried out by the NATO military forces.

The reader may wish to consult other published papers as additional background, but there are few papers which provide general descriptions of mission planning systems, although [1.2] is useful in this respect. Most papers at recent symposia, e.g. [1.3], describe only the computational approaches to route planning; this represents only a part of the total mission planning function. There is also a lack of papers which discuss the Human Factors aspects of mission planning and the problems associated with the sharing of tasks between man and machine, although [1.4] does acknowledge the joint contribution of computer and human operator to the total task.

1.2 INTRODUCTORY DISCUSSION.

1.2.1 Other Investigations.

Two surveys of mission planning systems deserve mention. In the first of these, Anacapa Sciences (sponsored by General Dynamics) conducted a review of relevant literature in order to compile a comprehensive list of specific information variables that must be considered during mission planning [1.12]. These variables were integrated into a task-oriented model of mission planning and reviewed in order to attain a pre-flight mission planning model. At the highest level, Anacapa identified 7 tasks:

1) assimilate target and weapons data
2) review threat and weather data in target area
3) specify attack profile
4) optimize flight route
5) select aircraft configuration and procedures
6) review mission plan
7) transfer system data to aircraft.

Each task can further be divided into subtasks. The Anacapa approach proved to be the most extensive inventory on pre-flight mission planning functions.

The second survey was carried out by the NATO Air Force Armaments Group (NAFAG) which in 1990 distributed distributed a questionaire to collect data on the status of Mission Planning Systems; 19 replies were received on systems that were actually in use or were scheduled for introduction within the next few years. Conclusions of these enquiries that proved relevant to this Working Group are summarized below.

The NAFAG enquiry concentrated on:

1) supported aircraft types

2) included planning functions
3) users of the systems
4) system suppliers
5) data files
6) external interfaces
7) time lines

Operational mission planning systems supported [illegible] different fighter aircraft types only. All mission planning systems in this inquiry were intended for use at or below airbase level, be it by different actual users:

- Wing Intellingence Officer
- Wing Mission Planner
- Squadron Mission Planner
- Navigator / Observer
- The pilot
- others (meteo, TAC command, army liaison, weapons specialist)
- or a combination of these.

Some systems are interfaced with systems of a higher C&C level.

The NAFAG enquiry has yielded that data files include data on weather, weapons ballistics, aircraft performance, intelligence, threats, terrain elevation, terrain features, electronically stored maps. Some systems contained none of these data; updating of datafiles could be performed manually or automated. The planning of tactical missions requires capabilites on route planning, penetration analysis, and weapon delivery. All systems in NAFAG's enquiry included the route planning functions that were described as time of flight, turn points and navigational references; altitudes, fuel consumption and range calculations. TACAN-frequencies and locations were included in most systems. Penetration analysis and weapon delivery calculation functions were included in most of the enquired systems, but some systems did not include any of these functions at all. This wide variety in the capabilities of mission planning systems is caused by the lack of a unique definition or specification of capabilities that constitute a mission planning system.

1.2.2 The Changed Military Scene.

With five months to prepare the first missions of the Gulf War, the air war went exactly as planned: pilots had sufficient time to rehearse their first missions extensively and adapt plans according to these rehearsal sessions. For this reason the lessons of "Desert Storm" are not necessarily applicable to other regional conflicts which may occur in the future. Moreover, there are differing views on the value of some of the equipment deployed in "Desert Storm". For example, the A-6E SWIP part task trainer was extensively utilized by A-6E SWIP squadrons but published accounts of its value range from "extremely valuable" to "deficient"; this points to the need for more careful analysis of the usefulness of such equipment.

"Desert Storm" has also been the first example of a war of the new concept including the deployment of forces from several NATO nations. The importance of interoperability in the design of mission planning systems arose during the conflict: interoperability experiences have not been encouraging. For example, it required a Herculean effort to cobble together a network that would enable US Navy ships in the region to receive intelligence data from the US Air Force.

Phase Two of the Working Group's studies was carried out during a period in which profound changes were taking place in the international scene. The most significant of these was the collapse of the communist regimes in Eastern Europe and the associated break-up of the military forces of the Warsaw Pact. During the same period occurred the operation known as "Desert Storm" in the Persian Gulf. Because of these the role for NATO air forces of the future has been the subject of intense debate, and at the time when this report was prepared the debate was still underway. What is quite clear is that the scenario for which much previous military planning was aimed, that of an intense battle between NATO and Warsaw Pact forces in Europe, is no longer considered to be a major potential threat situation. Much more important for planning purposes are likely to be limited conflicts in regional areas elsewhere within the world, although the potential for future conflicts within Europe should not be totally ignored.

In terms of the requirements for Mission Planning Systems, these limited regional conflicts may differ from a major European conflict in several ways, of which the most significant are:

- In these regional areas the databases which are at first available may be inadequate for mission planning and hence need rapid upgrade, e.g. by the use of satellite and aerial reconnaissance.
- The amount of training and rehearsal done in these areas may be zero or minimal.
- Where missions have tended to be highly standardized, future missions may have to be of new, unrehearsed types and may need to evolve during the conflict. This, in turn, may require improved brief and debrief facilities as well as mission rehearsal capabilities.

These changes became apparent during "Desert Storm" and it will be necessary in planning for the future to take account of the lessons learned in that operation. As an example of this, the results achieved by the Airborne Battlefield Command and Control Center Phase III (ABCCC III) systems fitted in EC-130E aircraft [1.5] may be pointers to the future in overcoming the lack of fixed infrastructure and the need for rapid deployment. The need for rapid deployment of forces from several NATO nations also points to the importance of interoperability in the design of future mission planning systems.

"Desert Storm" has been the first conflict in which mission planning systems were used operationally. Because of the short preparation time, industries were unable to provide a sufficient number of "military hardened" systems, and "off the shelf" equipment had to be used instead. Despite the hostile climatological environment (i.e., dust and heat), it proved to be functioning well, however.

1.2.3 Technical Considerations.

The major technical topics which were identified in Phase One have been listed above. During Phase Two these were amplified and changed, in part because of further technological advances which took place and in part because of further studies by the Working Group. These are reported in later sections of this report, but mention is made here of some specific examples by way of introduction.

The main technical factor to note is the continued increase in computer power, which has been particularly evident in commercial systems including the very powerful work stations which are now available. This makes possible the development of a wide range of mission planning systems based on commercially available hardware and software, from small portable battlefield systems up to large systems which may be distributed over several sites and airborne platforms. Improved communications and standardized interfaces are essential for such networked systems. In this area commercial systems are also providing suitable technology, e.g. open systems, but these may not have adequate security for many military needs.

Standardization and interoperability continue to be important considerations, across both aircraft fleets and ground systems. Development of new mission planning systems which are only usable with one specific type of aircraft is surely unacceptable in the future, but different types of aircraft can have such different characteristics and different standards of avionics that making a single design of mission planning system compatible with a wide range of aircraft types may be impracticable. Difficult compromises will be necessary in this area.

During Phase One, the Working Group gave only limited attention to airborne mission planning. Further consideration has been given in Phase Two, and as an introduction to this a description of some of the current developments in this area is given in Section 1.3 of this report. Current on board programs such as the US Air Force "Pilot's Associate" seem not to have given adequate consideration to methodological compatibility between pre flight mission planning and the mission planning element within the on board system. There is a clear need to consider both elements in terms of the pilot tasking to minimize workload and confusion. Compatible data is essential.

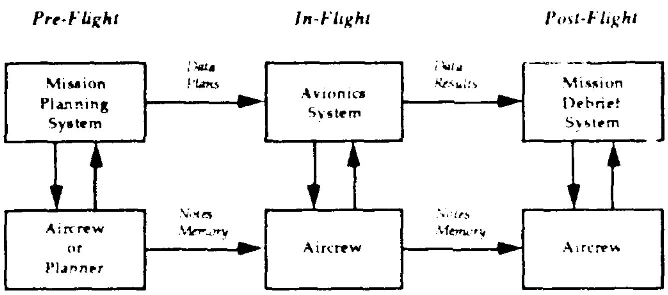

Figure 1-1. Transfer of Information Between Pre-Flight, In-Flight, and Post Flight Phases.

An alternative type of airborne mission planning is the ABCCC [1.5] in which a planning and command post having extensive computation and communication capability is flown in an aircraft which is operated at some distance from those aircraft which are executing the operational mission. This has the obvious advantages of greater planning capability and more crew availability than in systems such as "Pilot's Associate", against which must be balanced the disadvantages of the need for communications and the possible lack of up-to-date local information which may be available to the operational aircraft through its sensors.

For both the ABCCC and the "Pilot's Associate" the mission planner can be seen as one element in a larger system which incorporates other elements carrying out such functions as data fusion, command and control and communications. In some cases these may be carried out in different places. The definition of what constitutes a Mission Planning System then becomes rather blurred and the simple concept assumed in Phase One and described in AR-296 is too limiting.

Finally, it may be noted that using the simplest concept of a mission planner as an on-ground interface between ground systems and the on-board avionics system, the improved capabilities of future avionics systems may reflect back into the specification of the mission planner. As an example of this, more accurate navigation performance, such as will be obtainable from Navstar GPS systems, may eliminate the need for visual waypoints which in turn will affect the route-planning element of mission planning.

1.2.4 Human Factors Considerations.

It hardly needs remarking that human factors considerations are an essential part of the design of mission planning systems and yet, as was noted above, there are few references to this in published papers. This Phase Two report examines the topic in some detail in Chapters 3 and 4. As well as the more detailed problems of interface design, the designer of mission planning systems should also address the broader problems of whether the system is intended to be operated by aircrew or ground staff and, in the former case, whether the planning process is also intended to provide the crew with an element of briefing for the mission.

Figure 1-1 illustrates the flow of information between man and machine and between on ground and airborne equipment. The data flow required in the transition between pre-flight and in-flight is clearly dependent on whether the crew has already interfaced with the pre-flight mission planner. An ideal mission planning system would, perhaps, generate and pass to the avionics system all the required information; this would unload the planning task from the crew. Similarly at the end of a flight, the information available consists of that downloaded from the avionics equipment, which may be passed through the mission planner for analysis, together with that remembered by the crew. Ideally these components should be complimentary, and the greater the information which can be output from the machine, the less will be required from the crew. Human Factors considerations of this kind suggest that the design of a mission planning system is closely related to the design of the aircraft's avionics system but, as was pointed out in 1.2.2, this is not easily reconcilable with the concept of interoperability.

1.3 IN-FLIGHT MISSION PLANNING.

1.3.1 Background.

The AR-296 Phase One report covered in some depth the current and emerging ground-based mission planning systems, but only briefly mentioned in-flight mission planning. This section of the introduction chapter provides further information on in-flight mission planning, and includes brief descriptions of research programs currently being undertaken in several countries.

Discussions on in-flight planning of tactical missions raise questions like:

- if different people contribute to planning one mission, who is taking account for which part?
- a model to which an automated planning system operates should match as closely as possible the pilot's own cognitive model of the planning process, but what are the components of this planning process, and what's the related cognitive model?
- which part(s) of the planning process can be performed by a pilot, which parts require specialist planners, which parts can be automated?
- if (part of) the planning is automated, how is it achieved such that pilot and/or planner have trust and confidence in the results of this automated planning: does this apply to all planned aspects in a similar way (i.e. outcomes of fuel calculations probably need little discussion, but what about advice on avoiding missiles?)

A framework for answering questions like these is needed prior to implementation of (sub)tasks (sometimes referred to as "functions") in automated systems. The design and development of such sophisticated systems generally proceed through a logically ordered series of phases each of which builds on, and is much more detailed than, its predecessor. For standardization purposes, these phases may be laid down in agreements. One example of such an agreement is STANAG 3994, which aims at standardizing methods for the integration of human engineering procedures into the design and development of advanced aircrew systems.

An example of drawing such a framework is the first phase in STANAG 3994, "Operations Analysis": "Based on the predicted operational requirement, the system missions shall be analyzed to identify those factors which dictate the performance requirements of the man-machine system. Such factors include the sequence and timing of major events, threat situations, communication, environmental conditions etc."

In 1986, AGARD GCP Working Group 7 published [1.6] an inventory of the tasks and activities that have to be performed by a pilot in-flight. One of the tasks of Working Group 7 was the "identification of functions at the man-machine interface which are most promising for automation and areas needing additional research". The preface of [1.6] states that "Basic questions therefore are what information does the pilot really need and what control and management functions can be automated and what functions must the pilot retain to perform his task satisfactorily in relation to different mission aspects."

In order to analyze these tasks, Working Group 7 considered military helicopters, fixed wing air-to-air aircraft, fixed wing air-to-ground aircraft, V/STOL air-to-ground aircraft, and their defined operational scenarios. For each, mission task lists were prepared. A large number of functions to be performed within the different phases of the four examples were identical or, at least, similar. The functions were grouped into phases:

1) Planning, i.e. basic preparation of the pilot (briefing, evaluation, planning of route and attack, procedures)
2) preflight activities (inspections, checks, mission data loading, and taxying)
3) launch (take-off, climb and cruise, including sensor activation, setting, monitoring and checking of systems and displays)
4) ingress/egress
5) attack
6) recovery
7) post-flight debriefings

From a detailed analysis of crew tasks, Working Group 7 derived recommendations for automation at the control and display interface. For this analysis the crew tasks were grouped into three categories:

- control tasks (i.e. flight control)
- management tasks (i.e. navigation, threat management, systems management)
- combined management/control tasks (i.e. combat and weapons management)

In-flight planning is a management task, and here the current Working Group 15 activities fit into those of Working Group 7.

The goal of automation is to off load from the pilot tasks that he cannot perform adequately because of time constraints, demands by other tasks, the need to process too much data or similar limitations. A major risk in the automation of military aircraft is loss of the flexibility needed to handle a rapidly changing tactical situation when automation decisions have been locked into the system by the designer. Ref. [1.6] proposes to reduce this loss in computer-based avionics systems by providing the user with a choice of automation categories for control and display interface automation. Ref. [1.6] introduces as automation categories applicable to the control interface.

1) manual
2) manual augmented
3) manual augmented - limited
4) cooperative
5) automatic pre-select
6) automatic select
7) automatic autonomous

Automation categories applicable to the display interface are:

1) continuous
2) select
3) task feedback
4) external demand
5) system monitoring

Based on these automation categories and task categories, [1.6] makes recommendations on categories of automation for various task categories. Work similar to this has been carried out by Krobusek, Boys, and Palko [3.3] and is described in Chapter 3.

Some of the conclusions of Working Group 7 [1.6], may be applicable to activities related to in-flight planning.

A pilot's tasks are separated into:

- those providing continuous control over the aircraft flight path,
- all the discrete management tasks

When the pilot's workload becomes high, either

- the flight path control must be made easier to free a greater percentage to the management task, or
- the management tasks must be reduced in number or time to execute

Functional groups that seem promising candidates for automation are:

- various control tasks
- navigation and communication (needs to be expanded into what is best described as "situational awareness").

1.3.2 Current Research Programs.

At present, various companies, consortia and establishments are working on systems designated to enhance pilot situational awareness, decrease workload, increase weapon-system effectiveness, etc., aspects that have to be taken into account when addressing in-flight planning. These programs go by different names but they concern the concept generally referred to as "Pilot's Associate". Examples are:

- the US "Pilot's Associate"
- the French "Copilote Electronique"
- the British "Mission Management Aid"

All these programs focus on single-seater aircraft.

The principal requirements of these "crew assistant" systems are the automation of routine tasks and the provision of effective aids to the crew in solving problems and managing successful missions. Mission effectiveness should then increase because:

- the pilot is freed from various tasks and can concentrate on mission decisions
- he is given concise information relevant to the mission without saturating him with data.

The Pilot's Associate (PA) program (e.g. [1.7]) is an application of the Defense Advanced Research Project Agency's (DARPA) Strategic Computing Initiative. The initiative has as its goal the exploitation of new computing technologies such as Artificial Intelligence in general, knowledge-based / expert systems in particular, parallel processing architectures and speech systems. The PA program focuses on assisting pilots of single seat fighter aircraft (see Figure 1-2) and is planned as a high-risk, high-payoff effort that is not aimed at a specific flight vehicle application. The first phase of the program, System Development, focused on the technological development of a system capable of performing a set of functions that will assist pilots in operating aircraft and performing their combat mission.

Two contracts were awarded in 1986 for a three year "Phase One" development. One focused on air-to-ground scenarios and platforms and was lead by a team directed by McDonnell Aircraft Company. The second program focused on air-to-air missions and was headed by a team from Lockheed Aeronautical Systems Company.

Phase One of both programs was conducted in several stages, each with appropriate demonstrations, leading up to Demo 3 in 1990. At this point the systems contained the functional prototype capability envisioned for the Pilot's Associate, using near-term computing hardware applied to a model of a planned service aircraft. However the Demo 3 prototype still lacked the knowledge depth required for full functioning, and did not operate in real time.

The mission planner contained within the Lockheed Demo 3 system was implemented in C and hosted on a Sun Workstation. The route planning function included three linear dimensions but the time dimension was not implemented. The heuristically-controlled mission planner used the route planner to supply routes from which the pilot could make his selection.

Phase 2 of the Pilot's Associate program has now commenced with the aim of demonstrating a fully-functional system executing in a real-time, man-in-the-loop environment; this should be

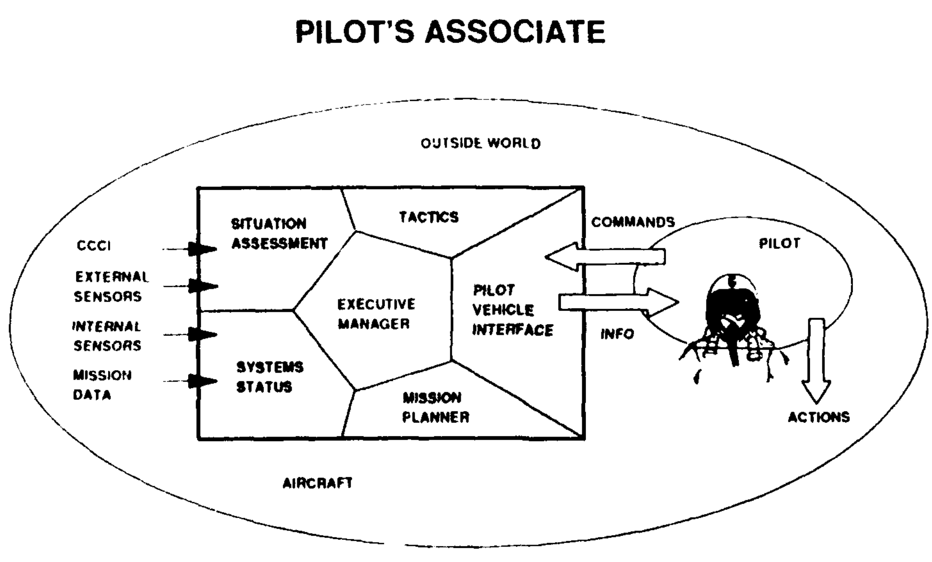

Figure 1-2. Block Diagram of the Pilot's Associate Architecture.

completed in 1992.

The Copilote Electronique is an ambitious project, initiated in 1986 by the Direction des Recherches, Etudes et Techniques and Dassault-Aviation, which aims to use Artificial Intelligence techniques to create an embedded system for decision aid in a single-seater fighter aircraft [1.8]. The objective is to provide the pilot with relevant information for decision aiding and so to enhance the global effectiveness of the mission.

The Copilote Electronique has to meet various constraints:

- it has to be able to deal with data that may be uncertain, incomplete or non-existing
- it has to take into account that data may arrive in an asynchronous sequence: lower priority activities have to be interrupted if new data referring to a higher-priority process arrive
- the Copilote Electronique has to guarantee the best possible answer to a problem in time: it is better to have a crude and incomplete solution in time than one that is detailed and fully elaborated but too late.

The concept of the Copilote Electronique distinguishes a hierarchy of reasoning levels. The reasoning level is decomposed into a reflection level ("niveau de reflection") and a decision level ("niveau decision") (see Figure 1-3). At the reflection level, the available data are manipulated. At the decision level, intentions are translated into considered actions or propositions for actions, and interactions with the pilot and the system take place. From bottom to top, the following levels can be distinguished:

- data (on resources, on systems, on the environment, from sensors, calculators, mass memory)
- reflection: evaluation of tactical situation and of mission plans, including pilot behavior ("comportement pilote")
- decision making (various management activities: system management, tactical management, mission management, and information management)
- Man-Machine Interface (MMI)

Major concepts (navigation & attack system, operational concept, nature of data) are aimed at implementation in the Rafale D aircraft. The model of the Copilote Electronique is at present being developed at Dassault-Aviation by interacting with an operational simulation.

Both DARPA's Pilot's Associate and Copilote Electronique use more or less the same modules; a major difference is the distinct hierarchy used in the Copilote Electronique.

The Mission Management Aid (MMA) Project is a collaborative research project between British Aerospace, GEC Ferranti Defense Systems, GEC Avionics & GEC Sensors, Smiths Industries Aerospace and Defense Systems and the Defence Research Agency. The four companies have worked together as the Industrial Avionics Working Group since it was formed in 1979. This group has for an extended period been working on the definition and high level design of a unified concept for advanced automation within an integrated avionics system known as the Mission Management Aid or MMA [1.9, 1.10]. The objectives of the Project Program are:

1) to establish the functional requirements and feasibility of systems such as the MMA
2) to prove the techniques for accomplishing this in a rapid prototyping environment and produce a set of functional specifications
3) to optimize the MMA functionality and develop the MMI on a real-time Mission Capable Simulation (see Figure 1-4).

The MMA incorporates the following major functional areas

- Sensor Fusion
- Situation Assessment
- Dynamic Planning
- Man-Machine Interface

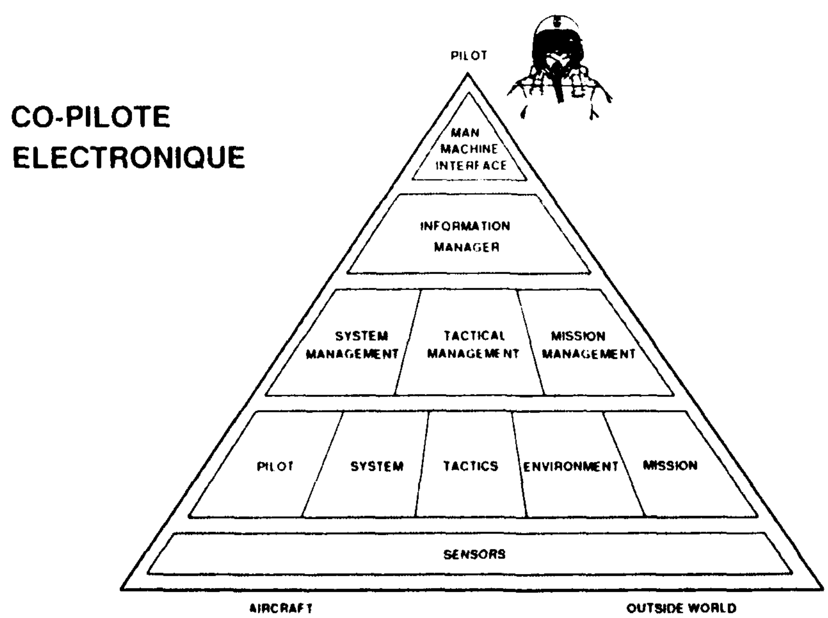

Figure 1-3. Block Diagram of the CoPilot Electronique Architecture.

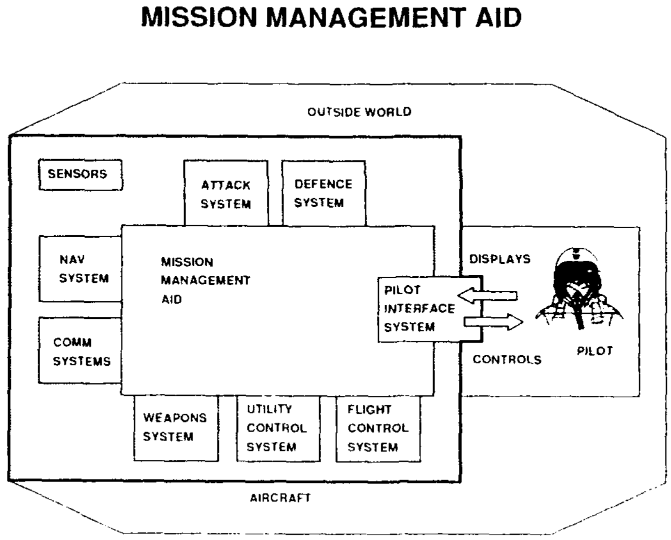

Figure 1-4. Block Diagram of the Mission Management Aid Architecture.

In the MMA concept, Sensor Fusion takes data from a number of sources including the on-board tactical database and combines it to produce a single fused view of the outside world referred to as the "Alpha Scene". This is combined with intelligence data from the pre-mission brief database to produce an assessed view of the situation (referred to as the "Beta scene"), taking account of the objectives of the current and future mission phases. This assessed view and the overall mission objectives are used to produce a number of tactical options (referred to as "Gammas"). Finally, the MMI function prioritizes the information presented to the pilot and manages the displays and multi-function controls.

After consideration of a number of possible missions and scenarios it was decided that to most fully exercise MMA's functionality the initial prototype should operate in an air-to-ground role, although the capability to carry out air-to-air missions will be incorporated in a later phase.

In endeavoring to define the allocation of function between man and machine it is important to develop an understanding of the capabilities of future systems: it is necessary to consider which tasks are best suited to the MMA and which to the pilot, how the allocation of authority for these may be influenced by the operational context and the need for duplication of function between the pilot and the MMA. Human performance is modeled on the basis of different levels of activity or response:

- skills
- knowledge
- inference

Skills are developed through extensive training and practice (e.g. flight control, weapon aiming). Skills are susceptible to disruption from competing tasks which may unexpectedly assume a higher priority. Unlike the machine, the human operator is very poor at multiplexing between tasks. Machines can perform these tasks with an accuracy which is only effectively limited by the resolution of the sensor data, power/speed of the processor, etc. An example of activity that is based on knowledge or previous experience is the response to threats. Humans are generally good at this activity while machine performance, on the other hand, is usually adversely affected with increasing data. Inferencing is the ability to reach a decision or to take a course of action based on incomplete data, and requires some level of reasoning or projection about possible outcomes or alternative solutions. Humans are particularly good at this activity.

The techniques required by the core functions of the MMA are currently under development in the prototyping phase. The MMA Project will establish a flexible real-time Mission Capable Simulator embodying the MMA. The objectives of this simulation facility are to allow the objective optimization of the MMA/MMI prototype functions in a realistic environment and to investigate the relative efficiencies of various methods of information presentation and pilot interactions with the system.

All three research programs share the philosophy that, in the future, machines will carry out routine tasks and compute tactics, relieving pilots to concentrate on the higher level tasks they are better qualified and trained to do. A pilot's role on the aircraft will change from that of an operator to that of a manager. Each program, however, defines its own "modules", "core functions", "decision levels", "levels of task abstraction", or "functional areas" etc., making it difficult to compare and to match them mutually.

In the end, the crew assistant concept should provide the framework for pre-flight as well as in-flight planning activities. Major differences between pre-flight and in-flight are that system status activities are not required pre-flight, and that pre-flight activities are less time-critical.

1.4 REPORT OBJECTIVES AND FORMAT.

As noted above, this report describes the results of the work carried out by the Working Group during Phase Two of their studies. It is hoped that it will be useful to a wide range of readers in the NATO community, including potential users of mission planning systems as well as those engaged in research and development.

As will be clear from the text which follows, future developments in the field of mission planning systems could take place in many different ways, depending upon both technical developments and the future needs of the NATO air forces. Because of this wide range of possibilities, and the way in which the various technologies and requirements interact together, it has not been possible to produce a report which shows a logical series of developments culminating in a design appropriate for some future application. Neither has it been possible to make a logical separation between System Concepts and System Techniques as was attempted in Chapter 8 of AR-296. Thus the techniques and the systems descriptions which follow have been grouped into chapters in as orderly a way as possible, which it is hoped will enable the reader to gather together the information most appropriate to his own problem or his own area of technical interest.

Following this introduction, Chapter 2 describes some of the wider issues involved in the overall design of mission planning systems. Chapter 3 deals with the vital subject of Human Factors and leads into Chapter 4 which is concerned with the new technologies in the man/machine interface area.

The various emerging technologies in the field of computation are described in Chapter 5, and some important areas in which computation is applied in mission planning systems are the subject of Chapter 6. Chapter 7 covers a very important but much neglected subject, that of evaluating mission planning systems. Chapter 8 summarizes the principal conclusions of the Working Group's studies and identifies research and development topics which could be important for future mission planning systems.

Chapter 2
System Design Issues

2.1 INTRODUCTION.

In this Chapter we discuss mission planning system design issues that were identified during Phase Two of the Working Group as either major factors in mission planning system performance or as critical areas for ongoing research. We begin where the Phase One report left off by focusing on ground-based mission planning systems used by the pilot to plan the mission. Later we expand into what we believe to be the future growth areas of mission planning systems. These future areas include:

1) integrating ground-based mission planning systems into networks that can perform mission planning at higher levels in the chain-of-command (e.g., squadron level or wing level).
2) fully integrating ground-based mission planning systems into C^3I networks so that they may fully exploit the latest real-time information concerning the battlefield situation.
3) moving towards greater amounts of automation in the mission planning process itself, where the mission planner is able to perform more sophisticated planning functions that currently are performed by the human planner.
4) moving automated mission planning technologies from the ground into the aircraft.
5) applying mission planning technologies to the growing field of Remotely Piloted Vehicles (RPVs), Unmanned Air Vehicles (UAVs), and Smart Weapons.

In the remainder of this Section, we will discuss the critical system design issues associated with these five areas.

During the Phase One activity the Working Group identified 9 design characteristics that were important to consider when developing and evaluating a ground-based mission planning system. These characteristics are:

(1) Interoperability

(2) Database

(3) Communication

(4) Time

(5) Flexibility

(6) Ergonomics

(7) Deconfliction

(8) Mission Rehearsal

(9) Growth Potential

For Phase Two it was considered appropriate to reorient the discussion and concentrate more fully on the architecture of mission planning systems. Therefore, although these characteristics are still of vital importance, they will not be discussed as separate topics in this report, but addressed in the context of the five application areas of mission planning systems that were defined above. Many of these issued are stressed in other Chapters throughout the remainder of the report.

2.2 GROUND-BASED MISSION PLANNING SYSTEMS.

2.2.1 Functional Description.

In functional terms, a ground-based mission planning system is a system that allows all the available and pertinent information to be used to plan a mission to achieve certain objectives in an optimum or near-optimum way, and also allows data that describes the mission to be loaded into the aircraft. The earliest systems, and even some of those in use today, are no more than an assembly of printed data (maps, manuals, intelligence reports, etc.) together with a simple manually operated calculator that allows routes to be planned. These have evolved into the more modern equivalent that comprises a computer with various input/output channels and a range of peripherals such as displays.

The inputs to the mission planning system comprise data arriving via communication nets to which the system is coupled. Some of the data may be entered manually but it is anticipated that, increasingly, data will be in a form that can be directly input into the mission planning system computer. The principal output is the mission data to be loaded into the aircraft via cassettes or similar devices, or carried aboard by the aircrew in paper form. As mission planning systems become linked into networks, distributing mission data via the network will become an important requirement.

The interface with the operator is provided by various pointing devices, i.e., the mouse, trackball, digitizing puck, keyboard, and display. The keyboard is fairly typical and the display is now usually full color and of a higher resolution than provided in many workstations.

The use of Ground-Based mission planning systems by NATO countries has proceeded rapidly since the inception of the Working Group. However, it is important to note that these mission planning systems serve largely as a calculator and display device for the human planner. Other than a small number of systems that have a limited auto-route generation capability, there is very little in the way of automation. The generation of the plan itself is left to the human planner.

2.2.2 Ground-Based Planning Hardware.

The major hardware components of a ground-based mission planning system are:

- The Processor
- Memory Devices
- Color Displays
- Input Devices (mouse, keyboard, etc.)
- Output devices (printer, cartridge tape)

The capabilities of these components when integrated into a mission planning system are, for the most part, quite sufficient to meet performance requirements. In some cases the memory available may be insufficient to store the large amounts of terrain and imagery data used in the mission planning process, however, the continued advances in the areas of optical storage devices is expected to largely address this shortfall, and therefore significant research by the mission planning community is not seen as necessary.

One area of concern is that of color displays. Currently the resolution of color displays is not equal to that available from paper map products. This performance limitation will continue to limit automated mission planning systems in that mission planners will never completely forsake the paper world so long as they provide the better visual resolution. Displays are therefore discussed in greater detail in Chapter 4 where we discuss the Man/Machine Interface Technologies.

The most important aspect of trends in the area of mission planning system hardware does not concern required technical break through. Rather it concerns the ability to acquire the most capable hardware quickly and affordably. In the past, military organizations have tended to develop and procure their weapons systems using a process separate from the commercial world. Mission planning systems have been no different. The reasons for this separation were many, but unfortunately the benefits associated with military standard hardware came at a high cost.

In no area was this cost more obvious than in the procurement of military computer systems. The long design cycle associated with military systems (as high as 10-12 years) not only resulted in high costs, but also virtually guaranteed that a military computer system would be obsolete before it was even finished being developed. This situation, coupled with the explosive growth in the capabilities and low costs of commercial computer systems has started a trend by the services toward the use of commercially procured computer systems to support a wide variety of military applications. This trend will be especially true for mission planning systems. As reported in Aviation Week & Space Magazine

> ". . .Lt. Col. Tony Sharon, chief of the mission planning division at ESD [the US Air Force's Electornic Systems Divsion,] said the Air Force's strategy is to spend funds to create standardized software rather than develop customized computer hardware. . . ." [Aviation Week and Space Technology, June 10, 1991 Vol. 134, #23, p. 52.]

In fact, the trend towards the use of commercial hardware for mission planning systems is already underway. A large number of the currently fielded mission planning systems are built around commercially available computer systems (see Phase One Report Appendix A.) Indeed, mission planning systems were instrumental as an early user of commercial hardware, in identifving the benefits to be gained from the use of commercial hardware.

The major conclusion to be gained from looking at the hardware requirements associated with current ground-based mission planning systems is that:

- for the most part they will be addressed by the normal development processes taking place in the commercial world
- The trend towards using commercially available hardware will help address key issues such as interoperability, expandability, and modularity, as the commercial world has already taken major steps towards achieving greater hardware interoperability.
- special attention may need to be given to the areas of display resolution and printer resolution.
- In the future, as more and more of the planning tasks are automated, parallel processing architectures will become important to help mission planning systems meet their real-time computational requirements.

2.2.3 Ground-Based Planning Software.

While the prognosis for mission planning system design issues concerning hardware is quite positive, the situation for design issues concerning software is more critical. It is clear that the trend in the hardware area is toward commercial standards that should go a long way towards addressing the key concerns of modularity, interoperability, interfaces, and expandability.

The corresponding trend does not exist in the area of software, for although the military can share computer hardware with its civilian counterparts, the software requirements for mission planning are quite unique. Therefore, it is to the software arena that much of the research in the mission planning field must be addressed. It should be noted, of course, that these problems with software are not unique to mission planning.

2.2.3.1 Software Architecture.

An over-riding problem in the software area is the lack of standards which also appears to be occurring in the hardware area. The result is a tremendous number of stand-alone mission planning systems that can only be used for the specific aircraft for which they were developed. A major design issue for future mission planning systems will be to develop software architecture that separates the aircraft specific software from the aircraft-independent software. The aircraft-independent software can then be developed and maintained to support the complete spectrum of applications saving significant time and money. Some examples of aircraft-independent software include:

- User Interface Software for entering data (e.g., waypoints, navigation points, time-on-target, etc.) and for displaying data (e.g., maps, imagery, etc.)
- Threat computation models.
- Weather prediction models.

A major research objective for mission planning software will be to develop a mission planning software architecture that provides a common user interface and a common set of computational tools that can interface with aircraft specific software and models. Of particular value would be a design which enables an aircraft model of flight performance and weapon data to be plugged into a generic mission planning system in much the way that software libraries are used today in programming. Work is already beginning in this area by the US Air Force (AFMSS) and the US Navy (TAMPS).

2.2.3.2 Software Standards.

To support the development of a modular mission planning system software architecture it is becoming increasingly clear that software standards need to be adopted. A current trend in the commercial world is towards the adoption of the UNIX operating system coupled with X-Windows as the user interface software. Although there are other competing standards, UNIX/X-Windows appears to have the upper hand as of this moment.

UNIX and X-Windows (or some alternatively accepted standard) offer the potential to meet the modularity, interoperability, interface, and expandability requirements of future mission planning systems. In fact, several of the NATO countries are already looking towards the UNIX/X-Windows standard as the development environment for their next generation of work station-based applications. Again as reported in Aviation Week & Space Technology, Lt. Col. Tony Sharon indicated that for future US Air Force mission planning systems

> " . . . The new mission planning system will employ an open computer architecture based on industry standards such as X-windows and POSIX. This will make it possible to select a wide variety of engineering work stations to meet current and future needs for mission planning consoles. . ." [Aviation Week and Space Technology, June 10, 1991 Vol. 134, #23, p. 52.]

Despite the emergence of a possible software development environment standard, there are still many different software development environments used throughout the NATO countries.

The development of software standards and so called "reuseable software" to avoid costly duplication of effort is, of course, a problem that spans the entire software development community, of which mission planning is but a small part. It will be important for mission planning software developers to keep abreast of the latest advances in this area. In addition, it is important to keep in mind that although software standards may be emerging in the commercial world, it is largely a political question as to whether NATO countries agree to bind themselves to an accepted standard. In this time of reduced tensions, it may be more difficult to achieve this objective.

2.3 NETWORKING MISSION PLANNING SYSTEMS.

The capabilities of current mission planning system are primarily limited to planning the mission of a single aircraft. A major requirement for future mission planning systems will be to expand their capability to perform multi-aircraft planning and to integrate better into the C^3I network.

Advances in multi-aircraft planning by networking mission planning systems together offers the opportunity to address critical deficiencies in current mission planning system capabilities, particularly in the area of deconfliction, and battle-field coordination. The continued progress to integrate mission planning systems into the C^3I network will further enhance the capabilities of mission planning technology by reducing the time that the planner must spend entering data into the system and increasing the time available to plan the mission.

A major obstacle to this integration will be the issue of security and communication. Linking mission planning systems that reside in the field, with highly sensitive national intelligence databases will require significant advances in computer security. Even if the security issue can be overcome, communication will present significant problems in that the volume of data desired to support mission planning may stress the bandwidth of operational communication systems.

The Working Group recognized developments in this area to be important for future research. However, because the Working Group lacked extensive expertise in this area, we have few specific recommendations to convey.

2.4 FULLY AUTOMATED MISSION PLANNING.

The transition of the mission planning function from the ground, where it is a pre-mission activity, to the air, where it is an integral part of performing the mission, brings a whole host of new issues that must be considered.

2.4.1 The Mission Planning Problem.

Mission planning problems are complex and difficult for a variety of reasons. First, multiple (and often conflicting) objectives must be pursued in the face of a variety of both implicit and explicit constraints. *Representative mission objectives* include reconnaissance, re-supply, support and strike. *Implicit constraints* are constraints that are imposed by the vehicle design (e.g., its fuel carrying capacity, stores carrying capacity, performance envelope and subsystem capabilities). *Explicit constraints* are constraints that may be imposed by a higher planning authority (e.g., a required probability of survival or mission success, time or ordering constraints that may be imposed on the pursuit of specific mission objectives, navigation constraints, maneuvering constraints within the vehicle's performance envelope and constraints imposed by the time available to plan). The fact that planning must account for significant uncertainty in the planner's knowledge of the current and future "state of the world" (i.e., the state of the vehicle and its environment) also contributes to the complexity and difficulty of the mission and trajectory planning problem. Because of this uncertainty, the formulation of detailed plans too far into the future is generally a futile exercise. As a consequence, an onboard capability to replan the mission is essential for piloted as well as autonomous vehicle applications, especially in poorly characterized environments where long endurance is required.

The requirement to replan the mission in real time adds yet another layer of complexity and difficulty to the mission and trajectory planning problem. This requirement arises not only because of the uncertainty with respect to the current and future state of the world that inevitably prevails at the time the mission is originally planned, but also because of unforeseen contingencies requiring a response in real time that arise during the execution of the mission. For example, a higher planning authority may redefine the mission objectives or alter the constraints that are imposed on the pursuit of those objectives, the mission environment (threats, weather, etc.) might change, the vehicle might sustain failures or damage, or opportunities to accomplish additional objectives might occur.

2.4.2 Hierarchical Decomposition.

Within a mission planning system, the level of detail to which mission activities must be planned by a given planning algorithm is determined by spatial and temporal planning horizons. Over a short planning horizon, actions must be planned in great detail. In contrast, it is unnecessary, even futile, to plan actions that lie beyond a short planning horizon at the same high level of detail. Thus, there is a natural decomposition of the in-flight mission planning function into a hierarchy, wherein the planning horizon decreases and the level of detail at which actions are planned increases as one moves from higher to lower levels of the hierarchy. In the context of an aircraft mission planning problem, skeletal plans of the entire mission are constructed at the highest level of the hierarchy. At intermediate levels, near-term actions that are consistent with the mission flight plan are planned in greater detail. Finally, at the lowest level of the hierarchy, commands are generated for vehicle subsystems (e.g., sensors, vehicle propulsion and control systems) that execute the mission and ensure vehicle safety.

The hierarchical approach to decision-making decomposes a large problem into a number of separate levels or sub-problems, thereby reducing the overall complexity, ideally without compromising overall system performance. At the top level of the hierarchy the entire mission is planned using coarse (e.g., abstract) models. As one progresses downward in the hierarchy, the spatial and temporal scope of the decision-making functions decrease and the level of modeling detail increases. The partitioning of the problem into sub-problems, the specification of appropriate local performance criteria, and the modeling of the interactions among sub-problems are all part of an integrated approach to developing a hierarchical decomposition. An important goal of this decomposition is to maintain a balance in the complexity of decision-making effort across all levels of the hierarchy.

2.4.3 Mission Planning vs. Mission Management

The combining of mission planning with in-flight activity makes it critical to distinguish between mission planning and mission management and to develop methods for their proper interaction. Whereas mission planning functions generate the specific sequences of actions that define a mission plan, *mission management functions* monitor the current situation for events that may require a re-planning response, determine the nature of that response by defining the inputs to the mission planning function, and control the interactions among the levels of planning. The mission management function plays the role of an executive that:

1) monitors progress relative to the execution of the current mission plan and assesses the vehicle's ability to continue to successfully execute the current plan
2) monitors the current situation for changes in the state of the vehicle or mission environment that may necessitate a re-planning response
3) monitors any changes in mission objectives or constraints that may necessitate a re-planning response
4) determines the nature of the re-planning response by selecting the appropriate planning algorithms and defining their inputs
5) controls the interactions among the several levels of the planning hierarchy to coordinate the planning effort.

Note that for manned aircraft, it is desirable that the pilot perform the in-flight management function and for the in-flight mission planning to be automated.

The mission management functions, at each level of the hierarchy, must decide whether to continue to pursue the current plan that is being executed at that level or to replan. Given that a decision has been made to replan, inputs must be developed for the planning algorithms. In effect, those inputs define the problem to be solved by the planning algorithms. Included in the inputs are the constraints or resource allocations that must be satisfied by the plan (e.g., allocation of mission time, fuel, survivability, and weapons use) as well as the objective function that should be optimized in developing the plan (e.g., minimize lethality, minimize fuel, minimize time, maximize effectiveness). In cases for which there are multiple objectives, the management functions must establish the relative importance. Finally, given that re-planning must be performed in real-time, the management functions must decide how much time is available for planning and how the on-board computational resources should be allocated in generating a new plan.

Each of the monitoring functions described above provides information that is used to decide whether or not to initiate re-planning. *Meta-planning* literally translates to "planning about planning" and here refers to how the process of generating a new plan is controlled. Some elements of meta-planning relate to determining the level(s) of the hierarchy at which re-planning should be performed, deciding which planning algorithm to employ at a given level, and establishing the time allocated to generating a new plan. The last section of the paper proposes a method for modeling the planning process that provides insight into how to formulate a "control law" to insure stability of the planning process.

Mission management must be able to distinguish between small departures from the current mission plan that can be corrected by making small perturbations to that plan (e.g., changes in commanded airspeed) at the route planning level and significant departures that can only be corrected at the highest level of the planning hierarchy. For example, meta-planning may initially restrict the mission planning level by requesting that it first attempt to resolve any problems locally before attempting complete re-planning of the mission level plan. Discriminating between small and significant departures from plans generated at all levels of the hierarchy is a principal meta-planning function. For small departures, the mission planning software may be directed to initiate re-planning using the current plan, potentially reducing the time required to find a good new plan. For large departures, re-planning may begin with a default "empty" plan, requiring the new plan to be completely rebuilt.

In a hierarchical system, higher levels provide guidance to lower levels. In the planning system, the plans generated at higher levels define both constraints and objectives that serve as requirements for planning at lower levels. Mission management is responsible for translating that information into requirements for lower levels. At each subordinate level, those requirements must be properly interpreted for input to the planning algorithms at the subordinate level. In addition, each subordinate level must provide information to its superior regarding the status of the execution of the plans that are generated at that subordinate level. The primary flow of information within the hierarchy is that requirements drive the planning process from higher levels to lower levels, while the changes in the operational environment drives the planning process from lower levels to higher levels.

One of the primary objectives of the design of the architecture should be to make a clear distinction between reasoning mechanisms and control mechanisms, i.e., between mission planning software and the mission management software. The architecture should be defined in a manner that provides clean interfaces between the mission planning software and the mission management software. The major benefit of this approach is that it simplifies the already difficult task of designing the planning software by ensuring that mission management issues need not be addressed by the planning software itself. In addition the mission planning software can be packaged in a modular fashion that facilitates the insertion of new software.

In order to effectively replan a mission in-flight in real-time, the time allocated to the mission planning software for a specific planning task must be established by the mission management functions, as well as the objectives and resource constraints that define a planning problem. Indeed, every plan must begin at a point in both space and time that is reflected in its initial condition. Choosing that point in the future implicitly bounds the time available to plan. Thus, the mission management functions are responsible for coordinating the choice of an initial condition on the planning process with the planners at other levels. Furthermore, the mission management functions must decide which planning algorithms may be most appropriate given the available time to plan. Establishing the time to plan and associated planning initial conditions is a non-trivial decision-making problem, but one that is crucial to the overall performance of an in-flight mission planning capability system.

2.5 UNMANNED AIR VEHICLES.

In the past five Sections, we have described a growth path for mission planning technology and its applications. Perhaps the ultimate development of this technology will manifest itself in the area of Unmanned Air Vehicles. A vehicle can be said to have a degree of *autonomy* if it has some capability to sense its own state and the state of its environment and, based on this situational awareness, to plan and execute actions that are designed to achieve specific objectives under specific constraints. *Aut[illegible]ous vehicles* have a variety of possible aerospace, land and [illegible]ased applications. Their potential use as a force multiplier in a variety of military applications is of great interest. They have many possible nonmilitary applications in remote and hazardous locations. The development of autonomous vehicles, however, will require technology breakthroughs in vehicle, sensor, processor and actuator design. It will also require the development of automated planning and control systems that are capable of planning the vehicle's mission prior to its deployment, controlling the vehicle's state during the execution of the planned mission and re-planning the mission in order to accommodate contingencies that may arise during mission execution.

Chapter 3
Human Factors Considerations

3.1 INTRODUCTION.

The developments in computer processing power in recent years have led to the emphasis on factors such as speed of task execution, speed of data access etc., in existing and emerging mission planning systems. The importance of rapid completion of part of or the entire planning task has been a driving factor. In the more advanced systems the rapid processing capabilities have been integrated with other features such as intelligent navigation systems, risk avoidance routes, and suggested attack profiles.

Although these and other features are important in any effective mission planning system, overall mission planning systems (MPS) development has rarely been driven by the requirements of either pilots or planners but by the developing technology. This has led to a design approach that concentrated on generic mission models rather than on a specific application or the skill requirements of the pilot or planner.

Despite efforts to improve the useability of many MPS, human factor issues have not yet played a significant part in the definition or development of MPS, with little regard paid to the requirements of the user.

A consequence of this design approach is that although technology has improved some aspects of the mission planning process, full advantage of the technological advances available has not been made. There are still many aspects of current and emerging MPS that are technology rather than user requirement driven.

A more radical approach to the design of MPS would be that the design of the interface should become a driving factor, as it is this area that is becoming the main constraint improving mission planning effectiveness. The design should be based upon the man-task relationship rather than the task alone. The design of the interface should follow guidelines and principles that take into account the cognitive aspects of the task's interaction with the system as a whole. From this perspective, technology does not drive the design, it serves as a means to achieve the design aim.

A major implication of this approach is that the choice of technology may be derived from the definition of the man-machine interface. However, the theory of the man-machine interface based on the analysis of the cognitive factors being the basis for the design of the MPS, has not yet emerged among the numerous existing proposals.

3.2 TASK ALLOCATION: TRUST AND CONFIDENCE.

The initial systems design of any system, including MPS, must concentrate on the functional requirements, rather than on the selection of specific components that are considered necessary to achieve the desired functions. Once the functional description has been determined, the allocation of functions to the various system components can take place. Allocation of function can be described as the positioning of the boundary between the operators and the system hardware, in terms of the amount of processing to be performed by each system component. The problem of function allocation is accentuated by the ever increasing capabilities of the hardware components, which are developing capabilities that were previously only possessed by the human component. This inevitably leads to excessive demands for automation. This, in turn, has led to the legitimate concern that the strategy of automating all of the aircrew/operators tasks (which is perhaps technically feasible), is unlikely to provide the optimum human-machine system (Hollister, 3.1). Ill conceived introduction of automation, without a detailed analysis of the task requirements, may lead to overload/underload or undue trust that the automation will function correctly.

Over recent years much research effort has been directed towards defining the relationship between the man and the automated system. This has resulted in the development of concepts such as Operational Relationships (Krobusek, Boys, and Palko, 3.2). In this scheme ten distinct categories of operational relationship are defined. These range from OR'A', where the pilot performs the activity, to OR'G'3, where the system performs the action autonomously.

This general concept of dynamic task allocation, where the level of system autonomy is dependent on the task and the operator's needs, has been shown to hold potential for improving overall system performance over static task allocation. It is associated with the concept of the adaptive interface (section 3.4.4.) and offers potential for improving the future mission planning process.

If the tasks may be performed by either the operator or a computer, then the operator and computer must be viewed as a partnership, each with abilities that both overlap and complement. There is clearly a need for continuing research aimed at defining task sharing, to ensure future MPS will provide an effective cooperative relationship between operator and computer.

In designing future MPS, reference should be made to design standards such as the NATO Standardization Agreement, STANAG 3994 AI, The Application of Human Engineering to Advanced Aircrew Systems. Similar national standards/ agreements also exist. These documents describe the methods by which human engineering procedures may be integrated into the design and development process. Two further standards are currently being prepared. Air Standard Advisory Publication 61/116B provisionally titled "Human Factors Aspects of Mission Planning Systems" and STANAG 7044AI, "Functional Aspects of Mission Planning System Interface Design."

3.3 TRUST OF AIRCREW IN AUTOMATED MISSION PLANNING SYSTEMS.

3.3.1 Introduction.

Mission planning both pre-flight and in-flight are tasks that have been performed by the aircrew or in some cases by specialist mission planners. The development of mission planning systems that automate much of the planning process, particularly using AI techniques, removes much of the human element from this mission-critical process, introducing the question of the level of trust and confidence the crew have in the planned mission. Trust and confidence are necessary if the pilot is to rely on the MPS for assistance on decisions that are critical to mission success and survival, particularly if automated tasks are carried out by implied consent. A lack of trust will not allow the full potential of the man-system partnership to be realized and reduce acceptability of the system.

The level of trust that aircrew may have in a system is dependent on numerous factors which change over time. Muir [3.3] describes how trust changes but is initially dependent on the predictability of the system. Later on trust is based on dependability, where in difficult situations the system is seen to consistently provide useful information.

The level of acceptance and trust aircrew have in any automated system dictates the level of autonomy they are willing to allow the system and the operational relationship under which they wish to operate. An understanding of the requirements for trust and confidence in the design of the systems may be aided by understanding the factors that affect the level of trust aircrew have in any automated system. This applies to ground based, airborne and particularly embedded MPS which may be part of an integrated avionics suite.

3.3.2 Interface.

The interface, and consequential interaction, between the pilot and the system may be designed to encourage the development of trust and confidence. Such an interface should have such characteristics as:

- Feedback.
- Displaying confidence levels. If the system is able to assign a confidence level to a decision made, the pilot is then able to make a value judgment based on this and other information.
- Displaying the decision process when requested. The derivation of a decision should be displayed so as to be easily and quickly understood by the pilot, (including sub-decisions, weightings, etc.).
- Allowing the pilot to question a decision/plan. The pilot should be able to question or alter specific sub-decisions to view the effect on the final decision.
- Clarity of level of autonomy/operational relationship. The interface should unambiguously display to the pilot whether the locus of control is with the pilot or the system.
- Allow pilot override of system decisions. A pilot requirement of any automated system is that they have the capacity to override any of the systems decisions.

3.3.3 Logic/Reasoning.

The logic and reasoning employed or perceived as employed by the MPS can be a major factor in the level of trust in and acceptance of a system planned mission.

- **The model with which the system operates should match as closely as possible the pilot's own cognitive model of the planning process. This would allow the pilot to map the decision understanding and therefore acceptance of the decisions made.**
- **The system should be tailored to match an individual pilot's cognitive model, abilities and preferences. If individual differences are significant, for the match to be effective the decision making process should be tailored to individual pilots. This tailoring of the system could** be extended to include individual pilot's abilities and preferences.

3.3.4 Who Plans the Mission?

The level of trust and confidence the pilot has may be dependent on the involvement the pilot has in the planning process, either before or during the actual mission.

- What, if anything, does the pilot gain in terms of a 'model' that may increase confidence, when he plans the mission? He may gain an element of mission rehearsal.
- If this 'model' is lost does the pilot, therefore, have less confidence in missions planned by specialist mission planners. If so, is he less able to react effectively to unplanned events.
- Trust in the ability of others, specialists in MP, to plan the mission will affect the level of acceptability, level of autonomy and allocation of function. The optimum allocation of function between the pilot and the MPS must exist and be unambiguous.
- If the mission is planned by others, the interface should be designed to allow the mission to be rehearsed in some form and to enable the pilot to examine 'what if' situations. This feature requires careful consideration due to the knowledge gained subconsciously during the manual planning process. If the process is automated, such knowledge must be transferred by the system.
- There should be the capacity for the pilot to delegate planning tasks in terms of both quantity and quality. This must be reflected in the operational relationship between the pilot/crew and the MPS. This may be dynamic.

3.3.5 Development of Trust and Confidence.

How would a pilot gain confidence during the introduction of an MPS? He may gain confidence:

- If the system is seen to consistently produce 'better' plans than the pilot using the previous mission planning methodology. 'Better' may be difficult to define.
- If the pilot develops faith in the system's abilities and reliability over time.
- If the system produces plans quickly and in a format that the aircrew can understand as well as modify in-flight, during the initial part of the mission, during 'hurry-up' operations.

3.3.6 Introduction of the System to Develop Confidence.

How would the introduction of an MPS into service or to the pilot affect trust and confidence?

- Introduction, initially of the automated system as a support or decision aid, increasing in complexity and significance of the support and advice offered. Gradually, the pilot would develop trust as the system complexity increases.
- The system is seen to learn and develop using the individual pilot's knowledge. The pilot develops confidence in the system's abilities, which would be seen by the pilot as an extension of his own ability.
- The system evolves with the pilot's capabilities from commencement of flying training, e.g., the mission plan

may be tailored to the individual pilot's ability to fly at low level.

3.3.7 Training.

Training would play the major part in developing trust in a highly automated MPS, as training will develop trust and familiarity which are critical factors if the pilot is to accept the system.

3.3.8 Others.

Pilots are becoming more computer literate due to exposure to computers at school etc., and thus may be willing to accept and trust the automated systems that pilots of previous generations would have rejected. The capabilities, reliability, etc. of the system is passed on to the pilot by word of mouth from other experienced aircrew, i.e., the system develops a 'folklore'.

3.4 INTERFACE DESIGN.

The user interface of a MPS is the medium through which a user communicates with the system. The form of interface has a major influence on how a user views and understands the functionality of the system. Consequently the user interface can be thought of as those aspects of the system with which the user comes into contact both physically and cognitively. The physical aspects are dealt with in Chapter 4.

The user interface has a specific form of dialogue used to facilitate user-computer interaction. The dialogue enables the user to 'map' the task to the functionality of the system.

An appropriate and well designed interface allows the user to decompose the overall task into sub-tasks and map them onto the system's functions. An inappropriate or poorly designed interface requires the user to breakdown the task in an illogical manner and the ensuing mapping is prone to errors.

The essential element of interface design therefore involves the user's comprehension of the tasks and the users 'map' of subtasks. This, in turn requires an understanding of the users themselves and the influence on their behavior of the context in which they work.

A factor crucial in the design of the man-machine interface is to ensure that the interface is compatible with the planning processes, which may be dependent on factors such as national mission models, subjective models etc. The interface must also be flexible in responding to changes in requirements made upon it as the demands of the mission changes. To meet these requirements human factors must be incorporated in the design process at an early stage. A standardized method for the integration of human engineering procedures into the design and development of advanced aircrew systems is described in STANAG 3994 AI. Standards and guidelines have also been developed (e.g., MIL-STD 1472D), to assist in selection and design of Man-Machine Interaction (MMI) for both commercial and military applications. Their application to MPS is primarily with the MMI of ground based MPS.

Extensive research effort is carried out in the development of MMI for commercial computer systems. Such developments have an obvious direct application to ground based MPS. An equal if not greater effort is being directed towards the development of the pilot-cockpit interface (e.g., big screen displays). Such work is carried out as part of the integrated avionics development programs such as Mission Management Aid (MMA), Pilots Associate (PA) and Copilote Electronique. Such work should be considered when designing the interface of MPS.

3.4.1 Choice of Dialogue.

It has been said that selection of an appropriate dialogue is the most important decision made in the design of an interactive system. Dialogue can be described as the specific method by which the system and operator communicate and interact. The two basic principles in selecting an appropriate dialogue for any application are (i) know the user and (ii) know the task. The factors that must be considered are:

- *Purpose*. The purpose of the dialogue in MPS varies with the task, location and user (for updating the meteorological data held on the database, a data input dialogue is required).

- *User type*. The potential users of an MPS range from clerks, to aircrew, to specialist mission planners. Users may also be intermittent or regular users.

- *User role*. The role of the user may be active or passive. An active user of an MPS (e.g., a specialist mission planner) will enter data, etc. The pilot of a mission, planned by a specialist may be a passive user. Users may have both functions at different points in the planning process.

- *User intelligence*. The over or underestimation of the user's capabilities can lead to the wrong choice of interface. This may be a particular problem where an MPS may have users of different capabilities for which different interfaces are appropriate.

- *Working conditions*. Working conditions are important to dialogue. If the operator is under stress due to time pressure, the need to interrupt the planning task, etc. the dialogue should reflect these stressors. The environmental conditions and their consequences e.g., NBC conditions may mean that the operator will need to wear NBC kit, restricting vision and finger dexterity.

- *Level of user training*. Different levels of user training that may be expected of various users of a MPS should be considered when designing the interface. The provision and manner of help facilities should also be considered.

- *Type of data*. The type of data that is being manipulated will effect the dialogue used and the interface design, (e.g., Ground-based MPS will require geographical information to be manipulated).

- *Importance of data accuracy*. The input of target coordinates and fuel load require accurate input into the mission plan. The correct dialogue and interface design should reduce the chances of errors being made.

- *Source of data*. If possible, the dialogue and interface should be related to the form, organization and sequence of the input source, e.g., entry of mission data might be in the format of the tasking order.

- *Validity of data*. This may affect the dialogue if the operator is unsure of the data or its recency.

Traditional forms of user interface such as command languages, form-filling and question-and-answer etc., may still be appropriate for certain specific MPS functions, e.g., for the entry of meteorological data a form-filling dialogue may be appropriate.

Various forms of human-computer dialogue have been, and continue to be, developed. These include: (1) Direct Manipulation Interfaces (2) Ecological Interfaces and (3) Adaptive Interfaces (Intelligent Interfaces). Such interfaces or aspects of each may only be suitable for specific phases of the mission planning process.

3.4.2 Direct Manipulation Interface (DMI).

User interaction with DMI may be performed by the manipulation of on-screen graphics e.g., windows, icons and menus by a mouse or rollerball with WIMP interface (Window, Icon, Mouse, Pull-up/down menu). The interface is said to be easily used by both novices and experts. All users actions are represented on the interface and any change is immediately visible. By representing the system, DMIs can reduce the cognitive load of the user, as well as reducing the overall memory task by needing to remember fewer, simpler commands.

These characteristics convey a high degree of transparency to DMI, allow the user to deal only with the task and to not allocate unnecessary resource to the operation of the system. Thus such interfaces are able to reduce the cognitive effort required to perform the task, e.g., plan a mission.

DMI have the following characteristics:

- The object of interest is always on the screen.
- Any changes made by the user are immediately displayed.
- Physical actions are used to interact with objects.
- It is possible to reverse actions taken.

Such characteristics provide benefits such as:

- Novices may quickly learn the basic functionality of the system.
- Experts are able to work rapidly, use short-cuts, and may be able to define new functions and features.
- Knowledgeable but intermittent users may retain operational concepts.
- Users may be able to see if their actions are furthering their goals, and if not, they may be able to change the direction of their activity.

A DMI interface also encourages the development of a direct relationship between the operator and the system. This direct relationship is described as resulting from two characteristics; the "distance" and the "engagement".

"Distance" refers to the gap that exists between the user's goals and the way in which operations must be specified to the system in order to achieve the goals. "Distance" refers to motor-perceptual phases (described as the "gulf of execution") and to cognitive phases (described as the "gulf of evaluation"). The interface between the man and the system may therefore introduce a "gap" between the goals of the user, his knowledge and the level of system description provided by the interface. A DMI may also be configured to mimic the existing manual planning process.

"Engagement" refers to the sense of directly manipulating the objects of interest rather than via another medium i.e., the interface.

Another characteristic of DMI is that given the immediacy of feedback, the likelihood of making substantial errors is reduced and if made, errors can be quickly corrected.

However, there are disadvantages that may need to be considered. DMI cannot be configured as a highly automated system, or if automation is embedded within the system few of the desirable characteristics will remain intact. In any highly automated system the 'distance' between the user's intentions and goals, and the system increases so that the interface may have no direct influence on the system. The sense of engagement may also be reduced as a consequence of the user's unfamiliarity with the system's logic.

This means that, if the MPS is to be highly automated (e.g., to reduce the time needed to plan a mission) DMI may not be the most appropriate form of interface to employ. However, the beneficial attributes associated with DMI should be considered.

Many of the emerging MPS, e.g., AMPA, as well as future MPS will use DMI/WIMP type interface for ground based MPS systems and elements of the interfaces may be used in on-aircraft systems, e.g., F18.

The development of DMI and its application to MPS will continue.

In order to specify the characteristics of a DMI, consider an example of a typical route point insertion procedure. This may be divided into two applications:

- a DMI design for a ground-based MPS.
- an on-board version for in flight operations.

DMI in a ground-based MPS is basically a method of presenting to the operator a number of automated tools to be used in performing certain types of task. The core of the DMI is embedded in the software design, which is developed mainly on the basis of icons used by the operator to access different functions on a display.

It may be assumed that the MPS provides a high resolution graphic display (CRT or LCD) with a number of symbols overlaid on different images.

These images may be video or still frames derived from some form of mass data storage (e.g., Laser disks) or graphics generated by a graphics computer.

The primary characteristic of DMI design is that the functions are accessible to the operator at any given moment by selection of easy to understand icons. The operator can select a particular function by use of a manipulation interface (mouse, touch-screen etc.), in conjunction with a keyboard. Results of this action are immediately presented on the same display, automatically rearranging the icon layout as required.

1) Via the display the system asks the operator to enter aircraft type and weapon load. An icon would be available to present the permitted weapon load and configuration.
2) A large map of the operations area is then presented. The operator is able, by use of the mouse, to enlarge (zoom) the area of interest.
3) As soon as the enlarged area is presented, all airfields are highlighted and the operator is given the option to select a home airfield, landing airfield (if different from home) and a number of alternates.

4) The operator is now given the choice to select the first waypoint in the route.[1] A zoom icon may be available to assist the operator in selecting the correct waypoint. If a digital land mass storage system is available, the option of presenting the information on a particular point (e.g., height, type, visibility hints, etc.) may be included by selection of a dedicated icon.

5) The operator is now asked to input route leg altitude, speed and, if required, time on waypoints. The system automatically computes and presents leg duration and an estimated fuel consumption. This value may be corrected at the end of the planning process, when the recommended fuel uplift is presented.

6) As with (4), the operator now selects further waypoints. As new waypoints are inserted, the system automatically computes and displays the turn path from the previous waypoint to intercept the next leg. If the operator requires a specific course to a waypoint, this may be selected via a dedicated icon. At any step, if the operator forces a parameter that is in contrast with other requirements (e.g., a time over a waypoint incompatible with the leg speed required), the system highlights the anomaly, and may suggest suitable solutions.

7) On completion of the route insertion, the system computes fuel quantity required at take-off (taking into consideration the attack phase, not discussed in this example).

8) The operator is now able to alter the route as required and adjust any parameter in order to optimize the mission.

In an on-board MPS, the DMI will be designed to the same principles as the ground based version, but with differences due mainly to the limitations imposed by pilot workload during mission execution and state-of-the-art technology.

In fact, airborne display technology could limit resolution of the image, thus having some effect on icon design. Similarly, today display dimensions are usually in the 5"x 5" to 6"x6" range, again limiting the amount of information that can be presented. Also to be considered is the fact that on-board digital map generators are yet under development and film-based map readers are not adequate for the job.

In addition, pilot inputs to the system can be made normally using some form of joystick or Pilot Hand Controller (PHC) connected to a cursor on the displays and supported by multi-function keyboards. This, together with the environmental constraints of an aircraft cockpit, means that the manipulation of data on the display is likely to be more degraded than in a ground based application. Possible future devices such as eye pointing systems may overcome this limitation.

However, the in-flight use of a MPS will be limited in many cases to re-planning functions following the need to diverge from the planned mission. Since the need for re-planning comes in the vast majority of cases from a change of the tactical scenario or following some form of aircraft failure, the time burden on the pilot should require a careful design of the DMI in order to allow him to make correct choices.

The following example of a typical in-flight route replanning procedure can be made:

1) The pilot becomes aware of a change in the operational scenario that requires a change of the planned mission, e.g., the need to change the primary target (or, alternatively, the system becomes aware of the change and suggests the pilot modify the plan).

2) On a display available in the cockpit the map of the operation area can be accessed by the pilot. The pilot is able, with the PHC, to enlarge (zoom) the area of interest.

3) Pressing a soft-key available on the display the pilot requires a re-planning facility. The PHC can then be used to select the new target on the map. A zoom icon shall be available to help the pilot in selecting the correct point. If a Digital Land Mass Storage System (DLMS) is available, the option of presenting information on a particular point (e.g., height, type, visibility hints, etc.) should be included by picking up a dedicated icon.

4) As soon as the pilot selects the new target, the MPS tries to adjust the previously planned route in order to cope with the new requirement. If this attempt is successful, the pilot is shown the modified plan; if it is not possible to retain the planned route within a certain limit, the system informs the pilot of the need to select a new set of route points (possibly suggesting a suitable solution).

5) The pilot, moving with the PHC on the map display, inputs the new waypoints, then he is asked to input leg altitude, speed and, if required, time on waypoint. This can be done either by using a multi-function keyboard or with the PHC inside ad-hoc windows on the display. The system automatically computes and presents leg duration and an estimated fuel consumption. At any new waypoint insertion the system automatically computes and displays the turn path on the previous waypoint to intercept the leg. If the pilot intends to force a particular course to a waypoint this can be done by selecting a dedicated icon. At any step, if the pilot forces a parameter that is in contrast with other requirements (e.g., a time over a waypoint incompatible with the leg speed required) the system highlights the conflict and suggests to the pilot different values.

6) When the process of route optimization is completed, the pilot selects an appropriate soft-key and the new route is stored in the system memory and used for the rest of the mission.

3.4.3 Ecological Interface Design (EID).

A limitation of DMI is that of cognitive control. The planner devotes attention to the parameters and variables concerned with the mission plan. Attention is also required with the task domain, control of the interface, and possibly of the overall system. This may result in the reduction of resources available for the planning task. Depending on the time available, user expertise and the expected risk, attentional resources are predominately concerned with the preparation of the mission plan. This makes the unattended activities vulnerable to error. DMI may not resolve such errors, whereas EI is concerned specifically with such errors.

1 These process stages may be performed by the system. However, for the sake of this example, a manual step by step process has been chosen. As soon as the operator selects the waypoint, the leg from the home airfield to it is drawn on the screen, and length of the leg and associated data automatically computed and displayed.

The Ecological Interface Design (EID) deals with the theory of interface design, based on Rasmussen's [3.4] ladder model of control of behavior in complex tasks. The theory has much in common with that behind DMI, particularly as it recommends making the properties of the task domain apparent. For example, easier operation may be achieved when icons that represent the operation are used.

Important guidelines for the design of interfaces may be derived from the theory. These guidelines underline the need for the user to be able to make mental simulations, e.g., "what .... if" styles of reasoning of the tasks Such simulations are aimed at understanding the acceptable limits of performance, which factors involve the greatest risk etc. Immediate and continuous feedback as to the result of actions taken and their consequences are thus essential for the user. The interface should also take into account, where possible, all the uncertainties of the mission to be undertaken.

The principal aim of the EID is that the interface does not force the cognitive control required by the user to a different level than that desired by the user. It is necessary to take into account the fact that multiple representations are used by the planners for problem solving, each requiring information support. The interface should support the user's information requirements concerning the "current situation", the "target state" and the "action required".

Practically, an EID should consist of the same hardware as the DMI (Section 3.4.2.). The major differences are that the icons of the EID should be able to be enlarged to become windows incorporating an area (See note 2) in which particular parameters are changeable by the operator off-line, i.e., changing them shall have no effects on the process unless an "accept" command is given. The changing of these parameters should be reflected by modifying a "preview" area of the window itself, to improve the description of the results of the modification of each parameters.

To better understand this rationale and compare it to the DMI design, we describe the route insertion process already detailed in Section 3.4.2 as it could be dealt with using an EID.

1) and 2) are basically the same as previously seen.

3) As soon as the enlarged area is presented, all airfields are highlighted and the operator is given the option to select home airfield and the landing airfield (if different from home). He can then select alternate airfields selecting an appropriate window on which the airfield within a fixed range from the landing airfields are shown. Within this window an area shall allow selection of a different landing field and the associated fuel needed - turn over capability, and time implications are then presented. When the operator decides to select the appropriate landing airfield the selection is transferred to the complete format on the display.

4) The operator is now given the choice of selecting the first waypoint in the route. A zoom icon shall be available to help the operator in selecting the correct waypoint. If a DLMS is available, the option of presenting information on a particular point (e.g., height, type, visibility hints, etc.) should be included by picking up a dedicated icon. As soon as the operator selects the waypoint, the leg from the home airfield to it is drawn on the screen, and length of the leg automatically computed.

5) Now the operator is asked to input leg altitude, speed and, if required, time on waypoint. An appropriate window shall be available in which the pilot can input parameter value, and in which automatically computed leg duration and estimated leg and total fuel consumption are displayed together with suggested parameter values (e.g., best fuel consumption speed and height for a cruising leg). When the operator judges that these values are correct he accepts them and the leg is displayed on the full display.[2]

6) Operating in the same way as step 4, the operator now selects the next waypoint. On an appropriate window the operator is given the possibility of previewing the turn from the previous waypoint to intercept the next leg and to select a particular course to a waypoint. Any selection that is in contrast with other requirements (e.g., a time over a waypoint incompatible with the leg speed required) will not be allowed to be entered and the incompatible features highlighted to the operator. Again, when the choice has been made the MPS reflects the change in the route for immediate display to the operator.

7) The operator is now able to change the route as required adjusting any parameter he wishes in order to further optimize the mission. To do this, an appropriate window is displayed in which the change of any significant mission parameter is reflected on the whole mission, helping the operator in selecting the correct value.

In the case of an on-board MPS, the EID will adopt the same principles as the ground based version, with the conditions as seen in Section 3.4.2 for a DMI.

3.4.4 Adaptive Interfaces.

One of the most powerful methods of supporting the information processing at the inferencing level is by modeling the reasoning and decision making process. This is the objective of the adaptive (or intelligent) interface. The adaptive interface operates on a cooperative basis, where functions are shared between man and machine. These interfaces reflect the flow of information and locus of control between man and the system. Adaptive also refers to the support the system offers, adapting to the needs and capabilities of the user, by taking into account his limitations. Adaptive interfaces may therefore be particularly suitable for in-flight mission planning, where data fusion may be taking place .

Adaptive interfaces are aimed at optimizing operator performance only at the times when support is needed. This approach is an alternative to the concept of automating the entire task if the suitable technology is available.

This approach envisages automation as a "back up". A default level would be where all tasks are manual; automation will only occur when specifically requested by the operator or when the performance level is considered unacceptable. This approach to the design of automated support should result in models of interaction which take into account both the variation in task demands and the mental resources available.

A major interface design topic addressed by the adaptive interface is the issue of the transfer of control between the operator

2 This window can be an expansion of the icon itself when "clicked" or the access to a dedicated format. Particular care shall be used in order that the operator be always aware of the fact of being inside a "what....if" routine).

and the system, and the allocation of tasks. The interface plays an important role in organizing the distribution of activities. With such systems the interface operates as an executive assistant, whose key function is that of recognizing human limitations and organizing task agendas. Sub-systems monitor operator performed tasks and derive an assessment of the pyschological and physical performance, evaluate the complexity of the subsequent task, and produce a strategy on how to assist the operator. It can operate as an on-line expert system which through cooperation with other avionics systems may:

- receive information and requests from sensors, subsystems and operator.
- assign priorities.
- evaluate time criticality.
- schedule requests, messages and information into task sequences.

In order to reduce arbitrary decisions, the interface manager is envisioned as a hierarchical representation of goals, plans and actions. Therefore task allocation is based not only on a consideration of the current demands, but on the evaluation of impending problems.

As with DMI and EID interfaces, a typical application of an AI can be described. However it is essential to stress that while DMIs and EID require state-of-the-art technology, the AI requires forms, software and/or hardware that are not yet available.

AI requires some form of monitoring the operator's psychological and physiological status during the task. This may be done quite easily in some applications, such as learning aid devices, in which the pupil answers automatically presented questions which are used by the system to infer the pupil's knowledge gain and thus define the next set of questions. In the case of an MPS operator, the problem of the method by which the system understands the operator's cognitive status has yet to be developed. The complexity of defining such a system suggests that the use of an AI in MPS would be limited to high stress situations, e.g., in-flight operations.

It is assumed that the AI interfaces with all the onboard systems, and a user behavior model that allows the AI to monitor and assess the pilot's psychological and physical status during all phases of the mission has been developed. This will allow the system to decide if a stress situation exists and whether automatic intervention by the system is required.

By monitoring system status and the tactical situation, the pilot may be tasked by the sub-system to perform only very high priority tasks.

In a routine mission, the AI will continuously monitor a number of parameters, and using an embedded cognitive model of the pilots behavior, develop a strategy for future system intervention.

If a situation develops in which the AI decides that the pilot requires assistance, the specific information, the form in which it is to be presented and its criticality will be generated by the AI, alerting the pilot and suggesting a particular course of action. However, the decision to comply shall still be the pilot's own judgment, although more detailed information would be accessible to the pilot on demand.

Using the planning task described in Sections 3.4.2 and 3.4.3 adapted to an in-flight route replanning sequence using an Adaptive Interface, the following steps would occur:

1) Inbound to the target area, on a cockpit display, the planned route is shown by overlaying a map. The pilot monitors the route and other major navigation parameters. A monitoring system continuously assesses specific mission parameters comparing them with expected values.

2) If the system detects a failure in an on-board system which, e.g., reduces the available fuel, the system will replan the route, height and waypoints and time over target. The pilot is alerted by a warning and a display provides details of the failure and all necessary information needed to support the pilot in making subsequent tactical decisions.

3) The new plan is accepted or rejected and the mission continues.

4) On entering the target area and approaching the Initial point, the system may be alerted by an AWACS in proximity to the target that a SAM site has become active. The system decides that a different approach to the target is required in order to avoid the SAM danger area. Using the target information, the route replanning rules in the system and the terrain data available from the on-board Map System, the MPS may reassess the run-in direction and height, to make best use of the terrain masking offered by the area around the target. Due to the need to act immediately, the MPS replans the route and advises the pilot of the necessity and urgency. However, all information on the modified tactical situation and rationale behind the system suggested actions is made available, together with information on the confidence level that the system has in the changes made.

The AI concept is only a stage below that of full automation of mission planning tasks, and its intrinsic advantages are that the operator is confident that an "electronic associate" is monitoring his behavior, ready to intervene as soon as required. During normal operation the same system may act as an intelligent information retrieval system and, if interrogated, suggest alternative solutions to the current situation. In addition, since a dynamic allocation of tasks can be made available, the pilot can select at any moment which tasks are left to the machine and which are fully retained by him.

Fully fledged adaptive interfaces as yet may not exist but their importance in all aspects of cockpit automation ensure their inclusion in many research programs. A major difficulty encountered with such an approach is the reluctance of aircrew to accept such automated support.

Reasons for this reluctance are many, but on the understanding that this may be an area where the limitations of the system become most apparent, it may be concluded that this is an area where more research is required. Effort should be devoted to the understanding the coordination and communication processes between man and systems in multi-tasking environments.

The acceptance of decision support by operators is based on the capability to establish trust and confidence. A major problem is the paradox of allocating control and authority to the system, while final responsibility remains with the human operator. Thus research efforts should be devoted to the understanding of the modalities to increase trust and confidence. This may be carried out by:

- the improvement of operator capability to perceive the reliability and limitations of a decision support system.
- the modifications of the criteria by which trust and confidence are established.
- the improvement in capability of the operator-system to allocate functions to the system e.g., make transparent human limitations.
- identify areas where trust is failing, and the need to actively support and reinforce where necessary.

Mission rehearsal and "computer aided instruction" represent two examples of how to increase trust and confidence on planning tasks.

3.5 SOFTWARE TOOLS AND PROTOTYPING.

There is increasing development and use of interface design tools in the design and development of commercial civil computer systems. Such tools should enable the interface designers of MPS, (predominately the ground based systems), to produce more suitable and effective interfaces in shorter time scales and as part of an iterative design process.

3.5.1 Graphics Tools.

The use of graphics tools allows the user to create and manipulate on-screen graphics, e.g., windows, icons etc., as well as graphic objects such as dials and buttons. In addition to simply designing the layout - the representational aspects - the interface designer must link the screens, images, and text to the functions of the system, and sequence the images in order to describe operational aspects of an interface.

3.5.2 Modeling and Diagramming Tools.

Modeling tools can either be graphically based or text based, but in addition to merely allowing graphics or text manipulation, they may also check and maintain the syntax and semantics of the model. This gives the benefit that code may be produced from a syntactically correct model.

3.5.3 User Interface Management Systems (UIMS).

A UIMS frees the interface designer from the low level details of the interface while providing a set of tools with which to manipulate the elements of the interface. A UIMS may consist of three essential parts:

- graphics and text manipulation tools
- linkage function that defines the operational aspects and links the interface design to the functionality of the system.
- management function that controls the interaction during the running of the system.

UIMS are still under development and details of their method of operation have yet to be defined. However, their is little doubt that the individual elements of UIMS will come together to form a specific tool, particularly as development methodologies such as SSADM and initiatives such as MANPRINT recognize and highlight the importance of the interface design.

3.5.4 Prototyping.

An effective and appropriate MPS interface is the product of the interface being both a major component of the MPS design and as a result of an iterative design process. Iterative design has been facilitated by the ability to create and use software prototypes which simulate the functionality and operation of a system. A prototype should be cheap and take only a short time to develop, hence the use of the term rapid protoyping. A prototype interface is an interface that :

- actually works
- may be either discarded or evolve into the final system
- be built quickly and cheaply
- forms part of an iterative design process and which therefore can be modified and re-evaluated.

Commercial prototyping software such as VAPS and TIGERS are available which run on graphics workstations, while a more flexible alternative is to directly produce the prototype using C code and graphics libraries. Such systems allow complex and dynamic prototype displays to be generated. Simpler prototyping tools that may run on PCs, allow form-filling or DMI type interfaces to be developed.

Prototyping is an essential and integral part of the iterative design process and allows constant evaluation by the operators as part of programmed operator trials, which allows users to develop an understanding of, and confidence in, the new system. A dynamic prototype interface with which actual or potential operators can interact will encourage task expertise to surface, which can be fed back into the interface design. Prototypes can be used by the interface designer to elicit information from the operators on the most appropriate system structure and functionality, operation, required representations and operator support needs.

3.6 MISSION REHEARSAL.

The concept of mission rehearsal is becoming an increasingly important future capability in mission planning systems. The requirement to support this function and the impact on the interface requires greater investigation.

Rehearsal may take place as part of the planning process or as a separate function after the mission has been planned. Technology plays an important role in producing the requirement for mission rehearsal. Automation is reducing the active "hands on" participation of the planner and the cognitive model the planner would build up unconsciously during planning is lost.

Increasingly technology may assist the rehearsal of the mission by providing the systems capabilities to support rehearsal. This may compensate for the decrease in familiarization with the mission. To ensure the design of the interface is able to support mission rehearsal, the requirements for mission rehearsal and the implications for the planning process as a whole must be understood.

Rehearsal capabilities are already present, to some extent, in systems already in service or being developed. However they are part of the planning process and the rehearsal aspects are implicit. Development is directed towards more explicit support to the rehearsal process.

The high level of interaction that the existing MPS require means that the chosen solution is inferred from a set of heuristic rules which vary according to the mission plan. Planners adapt them to the known mission plan conditions, gain familiarity and, as a consequence, control of the mission.

Emerging mission planning systems allow a level of rehearsal to take place. For example, they may provide three-dimensional perspectives, others provide "out-of-the-cockpit" views with the ability to zoom in and out of the view. Another rehearsal function is the capability to "fly through" the route in faster than real time or slowly through difficult stages and quickly through less difficult stages. The role of the mission planner will undoubtedly change with the introduction of emerging planning systems, due to the introduction of capabilities such as mission rehearsal.

MPS should be capable of supporting mission rehearsal both during the planning process and after the plan has been finalized. Time availability and the type of man-system collaboration are the two main factors that affect rehearsal potential.

When time is available, planners pay conscious attention to critical aspects of the mission, and to evaluate possible alternatives. If the planner is able to choose from a number of alternatives, then he makes an implicit correlation between local detailed solutions and the global overall plan. This harmonization process is dependent on the level of interaction that a given planning system makes possible. Thus rehearsal can be considered a technique to assess a plan's suitability by taking into account significant factors such as e.g., tactics, threats, deconfliction etc., and for the planner to develop confidence in the plan.

The time available and the type of man-system collaboration are considered differently when the operational need for rehearsal after the mission has been planned are considered. A simple model which describes the interdependency between these two factors can be defined. The model is based on three dimensions, high, moderate and low time constraints and the modality of the system-planner cooperation.

When time pressure is low, the modality of the interaction between the system planning may be high. The automated support can thus be modeled accordingly e.g., by allowing the planner to assign tasks on-line and by allowing him full control. Rehearsal is therefore implicit in the process, since the operator is self paced.

Where the time pressure is moderate, automated support can be configured to offer pre-solutions based on constraints imposed by the planner. As a consequence, rehearsal capabilities may concern specific critical mission phases of the mission.

Where time pressure is low or moderate, the planner is directly involved in the planning process and the system provides rehearsal facilities where required. After the mission has been planned, rehearsal may take place on the ground before take-off or during the flight; during either time pressure may be high and operator system interaction may be low. As a result, the automated system may be configured to undertake most of the planning task.

This simple model is aimed at describing features that may be implemented into an MPS in order to support rehearsal. Mission review, where a mission is "re-flown" to review aspects of the mission may be another function of the rehearsal process. Another important characteristic is the level and quality of "realism" that is considered necessary. Where realism is critical full simulation facilities may be necessary e.g., US SOF MPS. The cost of such rehearsal/mission planning systems will ensure that are employed only for those missions, (or parts of missions), where such a level of fidelity is required.

3.7 INTELLIGENT TUTOR & TRAINING SYSTEMS.

The training requirements associated with the emerging MPS have not been addressed. One reason may be that planners do not see the need for an investment in training as the design of future interfaces should enable the operation without the need to use specific trained skills.

However, some form of user help in the form of "intelligent assistance" may be required. The assistance should be modeled on the user's past interactions with the system. Such "intelligent tutors" may be envisioned as personal tools for assessing capabilities, evaluating reasoning, evaluating progress etc.

The development of computer aided instruction represents an important step toward the realization of "intentional systems". Such systems arise naturally from adaptive interfaces. Concepts such as DWIM (Do What I Mean) are important in speeding the planning process without sacrificing accuracy.

The input of the mission planner is in the form of simple commands which activate prepackaged models of interaction. These are able to infer the required actions needed to carry out the sub tasks. The design of such intelligent assistance is a major challenge to future MPS design as it requires harmonization between the dominant technology driven design process and the understanding of the users needs.

Chapter 4
Man/Machine Interface Technologies

4.1 DISPLAYS AND GRAPHICS.

4.1.1 Introduction.

For all types of mission planning and mission rehearsal equipment the presentation of information to human operators is a key element in the total system design; this is equally applicable to equipment used on the ground, such as computer-based workstations, and equipment installed as part of the avionics suites of military aircraft. Of the ways in which information can be presented to human operators, visual presentation is by far the most useful since it is interrogated by a sensor - the eye - which can accept and interpret a much higher rate of information flow than any of the other human sensors. This section is devoted to an analysis of the various factors which are important to the design of display systems for mission planning systems, together with an assessment of the present state-of-the-art in such display systems. It concludes with recommendations for the research and development which will be necessary in order to achieve the advancements in display technology which are likely to be most useful in future mission planning and rehearsal systems.

A display system for a mission planning system can be considered, in its simplest form, as consisting of the three elements shown in Figure 4-1. There must first be a store of information, a database, which contains all of the information which may need to be presented to the operator. Then there must be a processor which, upon command from the operator, selects the appropriate data from the database and re-formats it so that it is in a form which can be input to the display. The third element is the display itself which transforms the output from the processor into a pattern on a display screen so that it can be seen and understood by the operator using his eyes as sensors.

The information displayed in mission planning displays is usually of two types, alpha-numeric (i.e., letters and numbers) and graphic (i.e. pictorial). In some formats, such as maps, a combination of these is shown. Because the presentation of alphanumeric information is relatively easy compared with that of graphical and combined information, only these latter will be considered in this chapter. The processor of Figure 4-1 is then of a special type often known as a graphics processor or image generator.

The three elements in Figure 4-1 form a chain along which information is passed, the chain continuing to include the operator's eyes as its final link (the further extension to the brain is not discussed in this section). To allow this chain to perform effectively it is important that the characteristics of each of the elements shall be reasonably well matched. Thus, for example, there would be no value in displaying information at a higher spatial resolution than can be resolved by the eye since much of that information would necessarily be lost. Equally, if the displayed information is of very low resolution, the potential of the eye as a receptor of information is not being used to full advantage, and in addition some discomfort may be caused to the viewer.

The designer of the chain can specify the characteristics of each of the three elements, within limits set by the available technology, to suit the particular requirements of the mission planning system. The characteristics of the operator's eyes are, however, already fixed and hence must dominate the design of the chain and ultimately affect each of the elements. For this reason these features are described briefly in the following section.

The eye's performance as a receptor of the visual scene is extremely complex and only an outline description is given here; for more detail the reader is referred to the many texts (e.g., [4.1]) on the subject. In the context of the design of display systems the following are the most important characteristics:

- Resolution / Acuity
- Sensitivity to Brightness
- Sensitivity to Color
- Sensitivity to Contrast
- Sensitivity to Flicker
- Field - of - View
- Stereopsis

Many of these characteristics are interrelated. For example the sensitivities to color, to contrast and to flicker are all strongly affected by the level of brightness of the perceived scene.

The ability of the eye to resolve detail is of particular importance. *Figure 4-2 is typical of the performance* which has been measured using normal healthy subjects; it shows the eye's resolution as a function of the overall illumination of the visual scene. For objects close to the visual axis of the eye the resolution at brightness levels of 1 cd m^{-2} is about 0.25 mr (about 1 minute of arc); this corresponds to the condition of the image being focused upon an area of the retina wholly populated by cones. The resolution falls off steadily from this central condition until, at 30° off-axis where the retina is populated entirely by rods, the resolution is only about 10 mr (about 30 minutes). This peripheral vision is achieved at lower brightness levels, is insensitive to color, and is more sensitive to flicker than the central region.

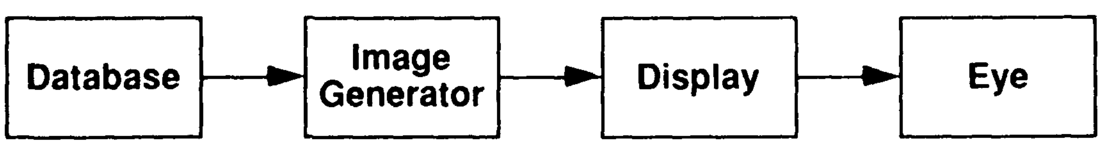

Figure 4-1. The Display/Graphics System.

Most displays appropriate for mission planning will be designed to match the flat part of the central-region curve, so that a display resolution of better than 1 mr should be specified. This resolution is normally required over the whole of the display because, although the eye's resolution falls off progressively away from the central region of about 100 mr diameter, eye movement and head movement are usually used by the observer to image any required part of the display onto the center of the retina.

Flicker sensitivity is important because, with electronic displays, the patterns written on the display surface must be periodically refreshed; if the refresh rate is sufficiently frequent the eye sees a steady display, whereas if it is relatively infrequent the display will appear to flicker. A refresh rate of 60 frames per second is usually specified and under most visual conditions this will be sufficient to prevent any perception of flicker.

Field-of-View of the eye itself may not be particularly important because of the rapid movements of the eyes within the head, and the rather slower movements of the head itself. Thus in designing most displays it is assumed that these movements are taking place even though the display surface may not subtend a very large angle at the eyes, since the eyes' optical axes are usually directed to areas of interest where the maximum resolving power is needed. For mission rehearsal, where the visual scene may need to simulate that seen from the actual aircraft, it can be important to use displays with very large angular subtends in order to create images which are seen peripherally.

Stereopsis is the ability to judge three-dimensional scenes using the different images seen by the two eyes of the observer. Some work (e.g., [4.2]) has been done to assess the use in simulators of displays which create a stereoscopic effect by presenting different images to the two eyes, but their value has not been established and few such displays have been used in operational flight simulators. *Stereopsis will not be considered further.*

4.1.2 Map Displays for Mission Planning.

4.1.2.1 Introduction.

The presentation of a map on an electronic display surface is normally done in a pipeline process which comprises the three main elements shown in Figure 4-1, database, graphics generator and display. The problem is greatly simplified, as compared with the generation of perspective displays which will be discussed later, by the fact that maps of the terrain and of terrain features are two dimensional. Once the map has been transformed from databse coordinates into display coordinates, further geometric transformation requires only the following:

- Scaling
- Slewing in two horizontal directions
- Rotation about a vertical axis.

The graphics generator may also be required to create symbology which may move fairly rapidly around the screen, but even allowing for this requirement, the task can be fairly easily met by many microprocessor-based computers which are widely available in workstations. In addition, for map displays used in future aircraft, the power of airborne computers is likely to be such that they can readily produce any type of map and graphics format required.

The principal difficulties in generating electronic map displays therefore arise within the other two parts of the pipeline, i.e. in the creation of appropriate databases and in the design of the

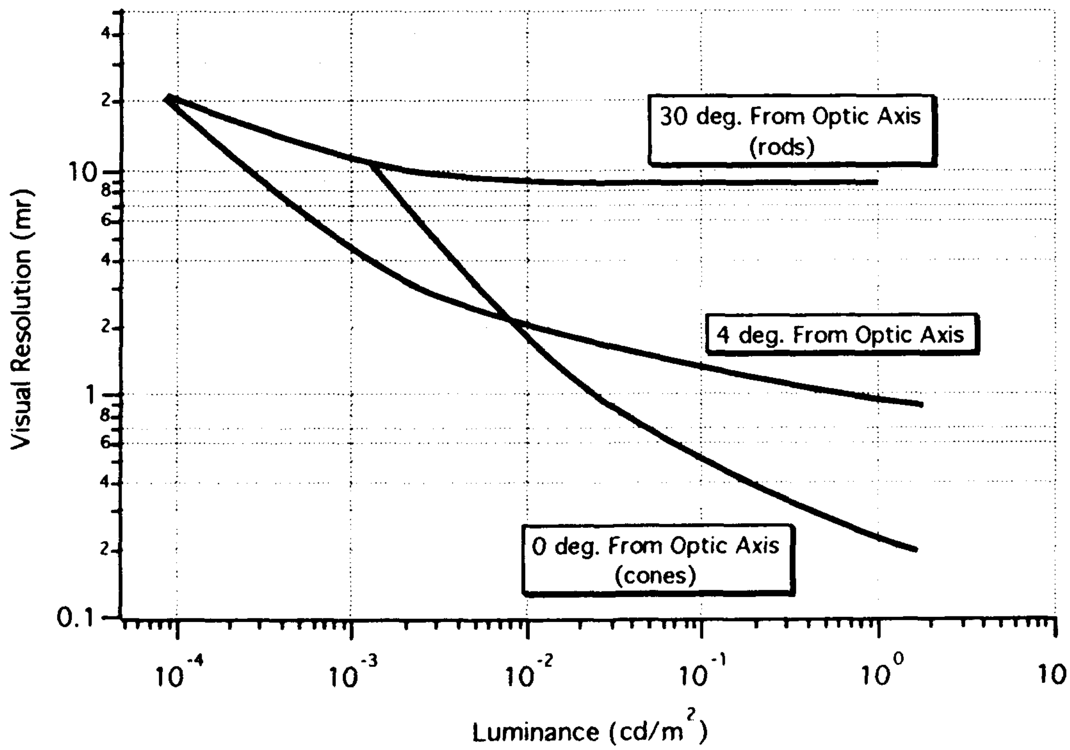

Figure 4-2. Eye Resolution.

displays themselves. These two areas are described in detail in the following sections.

4.1.2.2 Databases for Ground-Based Map Displays.

Digital Databases are now becoming available in many countries, and are being produced by both civil and military authorities as well as by industry. Although much of the data is available in formats which do not correspond to any internationally-agreed standards, such data can generally be readily transformed off-line into whichever formats are being used for individual applications. Prominent among the digital data available are the US DTED (Digital Terrain Elevation Data) and DFAD (Digital Feature Analysis Data), which can be provided in a range of different scales and accuracies, the most detailed corresponding to that of a 1:50,000 scale map. This is almost invariably sufficiently accurate for mission planning unless pin-point accuracy relative to individual buildings is required.

Mission planning requires that this data contains all the features which can affect the safety and success of the mission, and it is in this area that the most problems can arise. In a peacetime scenario it is unlikely that the data will be reliably updated in terms of power lines or other tall man-made features. In a wartime scenario, updating may be needed at frequent intervals to incorporate the positions of friendly and enemy assets; such information is generally provided from intelligence sources and is unlikely to be in a form compatible with the digital database information. Thus, to input intelligence information into a mission planning system generally requires significant manual operations. Future mission planning systems should provide the automation of this function to allow better integration into the C^3I network.

4.1.2.3 Databases for Airborne Map Displays.

For airborne map displays to be used for mission planning purposes, the required database information is generally no more detailed than for the ground-based systems discussed above. However, the problem of updating is significantly aggravated since the aircrew (unless the aircraft is a command-and-control center such as AWACS) is unlikely to have sufficient time for updating manually using intelligence information. Thus it seems likely that, except for very simple updates, the database must remain unchanged throughout the mission. For future systems updating of tactical databases via a data link will probably be considered mandatory.

4.1.2.4 Display Devices for Ground-Based Map Displays.

Electronic displays of map information which are to be used on the ground are almost invariably in a reasonable environment in which a fairly large display screen can be used and the ambient light level can be well controlled. This is also true of displays to be used in airborne command-posts such as the AWACS type of aircraft.

If maps are to be created which have a quality even remotely approaching that of conventional paper maps, the only technology which is currently available is the Cathode Ray Tube (CRT). The principal commercial application for high quality cathode ray tubes is that of engineering design, using Computer-Aided-Design (CAD) techniques, and this application has provided the business incentive to advance the state-of-the-art in high quality CRTs in the past decade. Although alternative technologies, such as liquid crystals, have also made notable improvements, it seems unlikely that they can seriously challenge CRTs in the foreseeable future. A typical high-quality CRT intended for CAD use might have the following principal characteristics:

- Full color (by using a screen with 3-color triads)
- Size 400mm horizontal, 300mm vertical
- Raster pattern (approx.) 1200 pixels per line, 1000 lines.

The total number of individual pixels (picture elements) which can be displayed is about one million, and if refreshed at 60 Hz to avoid apparent flicker, a video clock speed of about 100 MHz is necessary, which is currently possible with suitable drive circuitry. These circuits are now available as graphics cards which themselves contain significant computing power and memory to off load much routine computation from the main graphics computer. If the map scale is changed, or the map needs to be rapidly slewed, the response may be a little slow, but this is not normally seen as a significant problem in use.

A CRT of this size, when viewed at a typical workstation distance of 400 mm, will generate pixels which each subtend about 0.75 mr at the user's eyes; this is rather larger than the resolution of the eye, and hence the raster structure of the map display will be seen, and the picture will not appear as clean and sharp as with a good quality paper map. However, such displays do appear to be adequate for use in mission planning systems. Moreover, the advantages of an electronic map, such as ability to change scale, slew, rotate and select types of feature, are such that the map displays will inevitably be electronic in all current and future systems.

It is likely that future CRT's will be able to provide further increases in resolution and size. Displays of 2500 pixels and 2000 lines in sizes up to 500 mm by 500 mm are already in production, although they are not yet available to military standards. As high definition television becomes established, a sufficient market may be created to force prices of high quality displays (including the associated electronics) to fall significantly. This market may also provide the stimulus for the development of alternatives to the CRT, particularly for large screens designed for simultaneous viewing by numbers of persons.

4.1.2.5 Display Devices for Airborne Map Displays.

The problems associated with displaying maps in the cockpit of a military aircraft are considerable. Firstly, the size and position available for the display are far from optimum, the screen size being typically about 125 mm by 125 mm and the screen position being below or to the side of the central head-up display which inevitably takes the prime position in the pilot's field-of-view. Secondly, the cockpit transparency ensures that a high level of ambient light will often be present, and that sunlight can often shine directly onto the front surface of the screen. Thirdly, there may be significant vibration in the cockpit which will affect the resolution performance of the pilot's eyes.

Although some current map displays use optical projection systems to reduce the effects of ambient light and of vibration, modern practice is to provide very bright displays which are viewed directly. Such displays usually have much lower pixel performance than workstation displays; typically a raster pattern of 512 lines each of 512 pixels is used. It may also be noted that the color performance is seriously affected by the strong ambient light and by very low brightness adjustment (night operations) so that color discrimination by the pilot is degraded.

Much effort has recently been devoted to the improvement of color displays for cockpit use and new techniques are beginning to come into use, particularly liquid crystal displays, which in some respects give performance improvement over CRT's. Particular areas of improvement are size and brightness, the latter providing improved color rendition in high ambient illumination. But it is certain that the overall performance will always be considerably below that of ground-based displays.

At the other end of the ambience scale - night time operations - there is a different problem which arises if the pilot is wearing night vision goggles. These will significantly compromise his ability to perceive detail on a map display because they are monochrome and have a resolution capability far below that of the human eye.

Perhaps of more importance than display performance is the fact that a pilot must necessarily divide his time between several tasks and hence will not be able to concentrate his attention on an airborne map display for long periods at a time. Taken together with the performance limitations already noted, the result is that display formats have to be designed to be much more simplistic with a lower information content than those intended for ground use, and for this reason the design of airborne display formats has received much attention over many years. It is clear that the use of mission planning systems in the cockpits of future tactical aircraft could be significantly limited by the simple formats that will have to be provided on their map displays.

4.1.3 Perspective Displays for Mission Planning/Rehearsal.

4.1.3.1 Introduction.

The generation and display of perspective scenes is a much more complex and difficult problem than that of maps; the four main reasons for this are:

1) The geometric transformations which relate the displayed view to the terrain coordinate set can have six independent degrees of freedom as compared with only three for a map which is constrained to the horizontal plane.

2) If the display is to be used for real-time mission rehearsal, it is probable that the angular transformations will correspond to the orientation of the aircraft relative to the ground plane, and hence the maximum angular rates at which these transformations need to be varied must match the very high speeds of angular rotation which can be achieved by military combat aircraft. This problem becomes significantly more severe with the advent of helmet-mounted and eye-slaved displays.

3) The detail in the scene may be required to be much greater than in a map, particularly if the display is to be used for mission rehearsal.

4) The field-of-view of the display, as seen from the pilot's eye position, may be much greater than for a map display.

For these reasons no system has yet been constructed which generates a display which fully matches the visual scene as seen by a pilot flying a fairly low-level mission in a military aircraft. Nevertheless, the state-of-the-art has developed steadily during the past decade, so that images can now be generated in training simulators which are sufficiently close to the real-world scene to allow training to be carried out effectively. It should be emphasized, however, that there appears to be no rigorous experimental or theoretical basis which establishes the degree of visual fidelity necessary for different specific training tasks. Thus the visual characteristics for training simulators are usually based on previous experience of how well a similar task could be performed with earlier equipment, and also on the cost of the latest visual equipment available. As costs of computers have fallen, there has been a tendency for improved visual performance to be specified, even though the need for this has not been established in any exact way.

For future mission rehearsal systems there is effectively no previous experience on which to base decisions on the requirements for display characteristics, and it seems highly desirable that experimental research be directed at establishing relationships linking display performance and rehearsal effectiveness. However, it seems reasonable to assume that for those missions in which the pilot is relying heavily on interpretation of the detailed visual scene (e.g. in an attack upon a ground target which is identified visually) the visual scene should be as close to reality as possible. It is clear that there are potential dangers in rehearsing a mission with incorrect or inadequate visual cues, especially in parts of the mission such as target acquisition when such clues are likely to be at the limits of the pilot's eye resolution. It may also be remarked here that many simulator displays operate at such low light levels that the resolution of the pilot's eyes is significantly worse than in a high brightness real-world situation. Hence detection/ identification ranges in simulation may be quite different from reality, with corresponding differences in performance and workload.

In the discussion that follows, a low-flying mission will be analyzed and the demands of creating appropriately detailed visual scenes will be examined. It will be shown that the problems inherent in generating displays which fully represent the pilot's view of the real world are such that these displays are, for the present, impossible to manufacture. It is not yet clear whether or not mission rehearsal systems using displays of a lower standard will provide effective rehearsal performance.

4.1.3.2 Practical Specifications.

It has been noted in 4.1.3.1 above that no real basis exists for deciding the required performance for a visual display system for a mission rehearsal simulator, and also that for various reasons a fully representative scene is beyond the capabilities of any system thus far developed. Hence some compromise must be reached. Three of the key questions which need to be addressed in making this compromise are shown in the decision tree in Figure 4-3, and the answers have to be assessed in terms of their effects upon the components in the system chain as shown in Figure 4-1. The questions are:

1) Is real-time representation required? The answer to this question has a strong influence upon the speed at which the computations in the graphics generator are carried out, and if slow-speed or "snap-shot" reproduction of the visual scene is acceptable the cost and complexity of the image generator are significantly reduced.

2) Is hands-on capability required in the rehearsal simulation? The significance of this question is that if the pilot is to have the freedom to steer the aircraft through the simulated visual scene, the display must be capable of showing the scene from any position and any attitude. This precludes the use of "pre-computed" scenes which can be stored and retrieved at the required real-time rate. This again has a strong influence upon the complexity of the image generator.

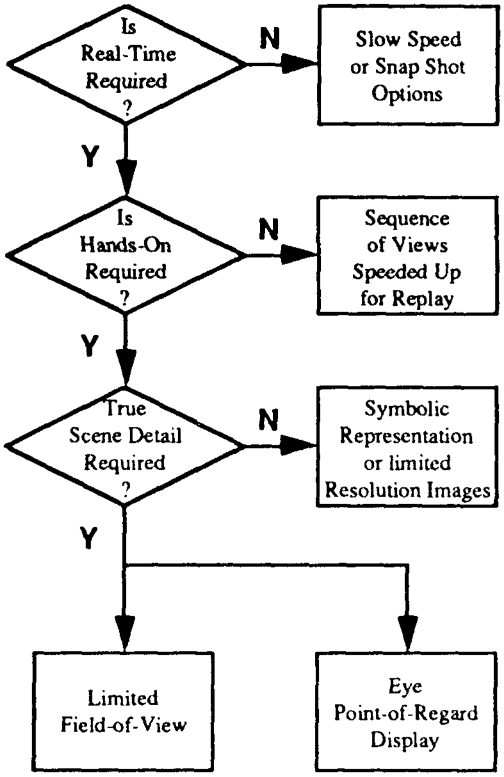

Figure 4-3. Visual Display Requirements for Mission Rehearsal Simulators.

3) Is true scene detail required? As there is no virtue in displaying a visual scene with more detail than the pilot's eyes can resolve, this question effectively asks whether scene detail matching his resolution is required. The answer has implications for each of the elements of the system chain.

There are many system options which can be chosen in response to these questions; these will depend strongly on the type of mission and also on the availability of data to construct the database which is holding all the information necessary to generate the visual scene. The information content in the earth's visual scene is much greater than in specific man-made targets such as aircraft. Thus the difficult missions to simulate are those in which the pilot has a good view of terrain detail from a low level.

In a fixed-wing low-level ground attack mission, the most critical phase and also the most difficult to simulate is that of target recognition and identification. Some simple calculations on the resolution requirements illustrate the problems.

If the aircraft is flying parallel to a horizontal ground plane at a height h, with the pilot's sight line depressed below the horizon by θ, and if the angular resolution of his eyes is r, then his perceived linear resolution at the ground is:

- Vertical Resolution = $rh/\sin\theta\cos\theta$
- Horizontal Resolution = $rh/\sin^2\theta$

The following values may be considered as representative:

- Height above ground = h = 100m.
- Angular depression = θ = 10°
- Eye Resolution = r = 0.5 mr

which result in the following values of linear resolution:

- Vertical Resolution at the ground = 0.3m.
- Horizontal Resolution at the ground = 1.7m.

It would be almost impossible to create a database covering an area representative of a typical target area containing terrain and feature detail equivalent to these values of resolution, and equally impossible to generate detailed images from it; further consideration of the implications are given in sections 4.1.3.3 and 4.1.3.4.

The third element in the visual system chain of Figure 4-1 is the display device; if this is to match the eye resolution value used above then the individual pixels on the display screen must have similar angular resolution at the pilot's eyes. Thus for a typical high resolution color CRT having about 1500 horizontal pixels the total horizontal field-of-view as seen by the pilot would be about 0.75 radians or 40°. A display of this size would probably be sufficient for the target acquisition task, but would not be adequate to provide the pilot with all the wider field-of-view cues which are necessary to properly perform the total flying task.

The difficulties of providing adequate visual scenes in simulating fixed-wing operation close to the ground become even greater in the case of helicopters. There are several reasons for this, the principal one is that operation can be even closer to the ground than at the height of 100m quoted above. It should also be noted that the crew is likely to be looking down through a greater depression angle than in the fixed wing case, perhaps down at 20°or 30° to the horizontal.

Using the same expressions, but with values of h=20m and θ= 30°, the corresponding values of perceived resolution are:

- Vertical resolution at the ground = 0.025m.
- Horizontal resolution at the ground = 0.04m.

These are such small values as to make it almost impossible ever to create moving visual scenes of this magnitude of detail. Perhaps, in the future, it might be possible for very small individual features such as buildings.

Another major difficulty with the simulation of helicopter operation is that because the vehicle can have quite small ground speed, the crew will look around through a relatively large arc of vision, much larger than in fixed-wing operation. Some helicopters have bubble canopies which allow a visual field of over half the 4π steradians solid angle visible by a totally unobstructed observer. A display which could provide sufficient pixels to give resolution of 0.5 mr over a field of view of 2π steradians would have to contain some $2.5\text{x}10^7$ pixels. This is much greater than any currently available display.

For these reasons, it has not, so far, been possible to design visual simulations of a quality really adequate for the training of low-level helicopter operations, and it does not seem likely that suitable equipment will become available in the foreseeable future. Practical experiments using currently available technology are described in depth in [4.3, 4.4]. Realistic simulation for mission rehearsal is equally difficult, with the added problem that databases may need to be created in a much shorter time scale.

4.1.3.3 Databases for Perspective Displays.

The creation and updating of databases for perspective displays is potentially one of the most difficult aspects of advanced mission planning and rehearsal systems, particularly if the display to be generated is to give a picture which is visually close to that of the real world. As discussed in previous sections, the worst-case is for tactical aircraft and helicopters operating close to the ground, because the required scene detail is much greater than for map displays, and this requirement forms the basis for the discussion which follows.

High resolution databases may be built up from the following:

1) Standard databases such as DFAD and DTED.
2) Reconnaissance Data from aircraft and satellites, usually in the form of images.
3) Libraries of standard features and textures which approximate to the features and textures in the actual scene being recreated.
4) Intelligence data.

The extent to which standard features and textures can be used instead of specifics depends very largely upon the height of the operating aircraft and the use to which recognition of the scene is being put; in target areas it may be found inappropriate to use them because they will be insufficiently representative of the real world.

The building of a complete database from these four types of data can be a difficult process. Amongst the reasons for this are:

1) The scale, resolution and coordinate bases of the standard digital data may not be the same.
2) Image data may have ill-defined coordinates and totally random directions of viewing.
3) Image data may have been obtained in different lighting conditions and have different cosmetic quality.
4) The synthesis of feature geometry from image data requires the combination of more than one image to obtain perspective information, or else the interpretation of shadow dimensions.
5) Features and terrain may not combine together in a way which is cosmetically satisfactory.
6) Intelligence data may be generated in a variety of forms which are likely to be incompatible with database standards.
7) Information provided from different sources may be inconsistent. Inconsistencies between the completed mission rehearsal perspective database and the simpler map database used for other mission planning functions could cause major problems during the overall planning process.

For these reasons there is inevitably a large amount of skilled manpower involved in the creation of a database suitable for the simulation of a low-level scene of a complex area of the ground with man-made features such as buildings. Because of the penalties of including more scene detail than necessary, they are usually optimized for specific types of mission and are not generally usable at significantly different heights. Ref. [4.5 - 4.7] provide excellent accounts of the techniques used to build databases.

The need for human judgment in the building of these databases implies that this is done ahead of the on-line creation of the displayed scene by the scene generator. However, with the development of mission rehearsal systems and the need to reduce database preparation times as much as possible, efforts are being made to carry out part or all of the building during run-time. So far, this has only been fully done with workstation-based systems in which DTED and DFAD information is directly used in the generation of scenes, but without the complexities of using additional data such as photographic images. However in the ESIG-4000 computer system being developed for a US Air Force mission rehearsal system, which uses image data as well, the features and the terrain are built up as two separate databases which are then combined in real-time; this is claimed to give advantages in savings of database preparation time for which a total of 48 hours has been specified to construct a database for a target scene which includes a number of highly detailed buildings and other features.

Databases must be constructed so that the data is stored in a format from which it can be extracted by the image generator. In many cases this implies that the format is specific to the design of the display generator and, since most manufacturers have their own individual designs of generators, the format is specific to each manufacturer. As an example of these differences, terrain data is sometimes stored in rectangular coordinates and sometimes by means of polygons. In addition, most data is stored using some degree of data-compression, and again the method used tends to be company-specific. For the users these are major disadvantages since a database constructed for one display system cannot be used for another without expensive and time-consuming re-formatting. An initiative has been taken by the US Air Force with the Project 2851 [4.8] which is trying to set standards for simulation databases, but the problem is proving to be extremely difficult.

All of the above discussion has assumed that the scene to be generated is a representation of the pilot's visual scene. For most missions which involve target attack it is equally important to simulate the scene which would be generated by a sensor, such as a FLIR, looking forward from the aircraft. Such scenes can be created from the same database as the visual scene but need additional parameters which characterize the IR behavior of the terrain and the features.

4.1.3.4 Image Generation.

The function of the image generator, as shown in Figure 4-1, is to take data from the database and to construct an image of the visual (or sensor) scene taking account of the geometry of the aircraft relative to the terrain coordinates. The output signal is fed to the display in a format defined by the display characteristics; usually the format is a raster standard specified in terms of the number of lines, the frequency or pixel content of each line and the refresh rate.

Although each manufacturer of image generators has his own design for performing this function, and these differ in detail, most conform in general layout to that shown in Figure 4-4. This figure shows at the left the combination of data into an appropriately formatted database, which is not really an image generator function and is usually carried out off-line, but which has to be considered as part of the overall design process to ensure compatibility of formats. The on-line pipeline system which forms the image generator comprises four processors which successively perform the following transformations:

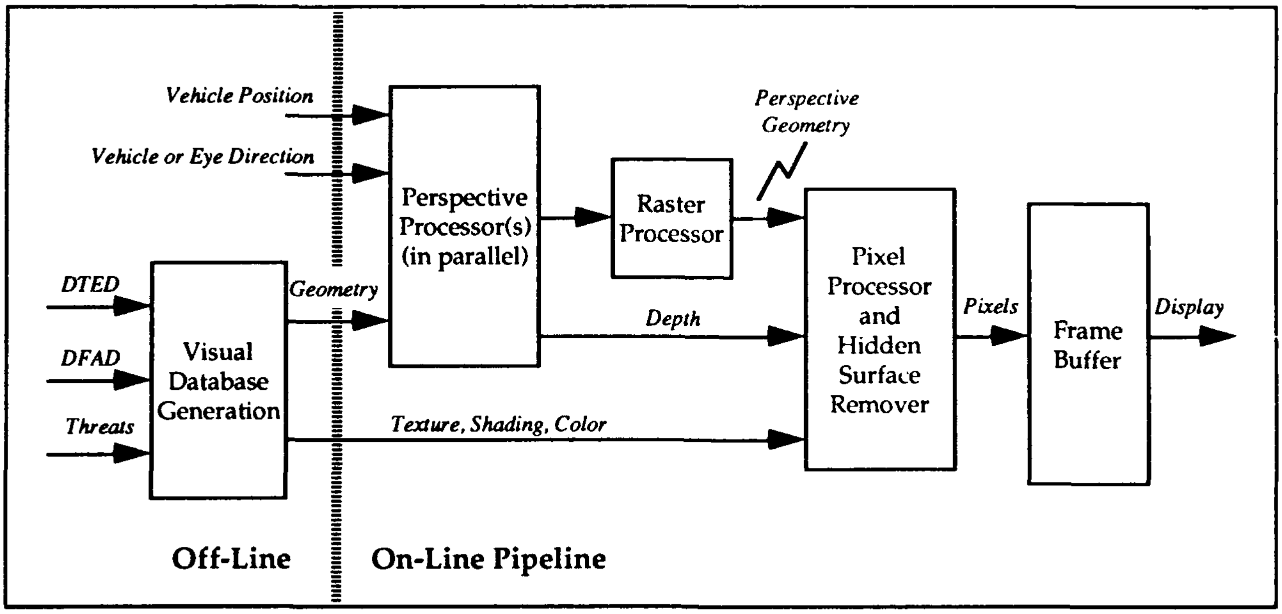

Figure 4-4. Typical Structure of an Image Generator.

- The Perspective Processor takes the database model and, using data concerning the geometry of the aircraft relative to the terrain, computes the terrain and feature geometry in display coordinates.
- The Raster Processor reformats the perspective geometry into the display raster format.
- The Pixel Processor takes the raster signal and, using depth data from the Perspective Processor, deletes information on surfaces which are hidden from view by nearer surfaces. Using texture, shading and color data from the database it calculates the pixel brightness and color for each pixel on the display.
- The Frame Buffer is a store in which all the pixel information is accumulated so that it can be read out at intervals determined by the display clock.

An estimate has been given in section 4.1.3.2 above of the number of display pixels required to give a display which is really adequate for low-level flight, but this is beyond the resolution of the best displays. As will be noted in 4.1.3.5, most raster displays have no more than $3x10^6$ pixels which need to be refreshed at 50 or 60 Hz to avoid perceptible flicker, and thus a pixel data rate of $1.5x10^8$ per second is required. In practice the data rate from even the most powerful image generators currently available, such as the GE Compuscene 5 and the E&S ESIG 4000 is less than 10^8 per second per channel so that parallel pixel processors may be necessary. Parallel operation of several perspective processors may also be required to provide adequate throughput.

The operation of four processors in pipeline necessarily implies significant time delay between a change of the input geometrical data and a change in the displayed image. Top-end systems have overall transport delays in the 60-70 ms range, and this is only just adequate to prevent the delay becoming perceptible to the pilot.

Although performance figures for high-quality, high-cost image generators have been mentioned, it should be noted that modern workstations are now so powerful, and have so much capacity for operating in parallel, that they are beginning to make significant inroads into the training simulator market. It is reasonable to predict that this will be followed by progressive inroads into the mission rehearsal area, but the extent of this is difficult to predict as there is, as yet, no clear agreement on the display resolution requirements for rehearsal systems. The use of workstations for rehearsal purposes within a mission planning system also based on similar workstations has obvious advantages in terms of first cost, compatibility of data standards and ease of maintenance and support.

4.1.3.5 Display Devices and Optics.

The third element of the system shown in Figure 4-1 is the display device which transforms the signal from the image generator into a visible image. Because of the need to match the eye's characteristics, the image should ideally be full-color, high resolution, wide field of view and collimated into the distance, but display devices to simultaneously meet this requirement are necessarily very complex and very expensive and, beyond some limitations, are not yet state of the art. More simple displays are sometimes used which may be adequate for particular tasks in training simulators, but the lack of any real experimental evidence on the appropriate performance levels for mission rehearsal displays makes it difficult to provide guidelines on the type of display which should be chosen for future mission rehearsal systems.

A brief description of some of the display types used in training simulators is given below; mission rehearsal displays will be similar and it is likely that training and rehearsal could be carried out on the same facility.

Directly-Viewed Displays. The simplest type of display creates an image on a single surface which is viewed directly by the pilot. To obtain resolution close to required levels combined with a reasonable field-of-view currently implies the use of a Cathode Ray Tube, although other display types such as liquid crystal screens are starting to challenge the CRT. The sizes and standards in use are the same as those already described in 4.1.2.4 as being suitable for map displays.

The main advantages of a simple display of this type are their cost and their compatibility with existing designs of commercial workstation. The main deficiency is the very restricted field-of-view which is likely to make it unusable for some types of mission, such as helicopter operation close to the ground.

Larger CRTs with up to 2000 x 2000 pixels are now becoming available although they are not yet sufficiently rugged for some military applications, but any directly-viewed single-screen display will always be seriously deficient relative to the likely requirements for mission rehearsal.

In some training simulators the CRT is viewed through a collimating optical system which, in its simplest form, can be a simple pancake lens. Although some realism is added by image collimation, there remains the fundamental disadvantage of narrow field-of-view.

Multiple Displays. Several alternative arrangements have been adopted in training simulators to provide more representative fields-of-view, and these are likely to be considered also by designers of rehearsal systems. The two basic options available are:

1) Several CRT displays mounted side-by-side and either viewed directly or through optical collimators.

2) One or more projection displays which illuminate a screen, often in the form of a dome, on which the image is focused.

The use of more than one display can be convenient in the overall system design since each display can be interfaced with a separate processor allowing the image generation to be shared between parallel processors. The main disadvantage is increased complexity and the difficulty in obtaining a complete visual scene with acceptable continuity between the separate images. The projection systems also suffer from generating brightness levels much below real-life.

Display systems of these types are used in almost all full-flight training simulators, and a dome version is the baseline choice for the USAF Special Operations Forces mission rehearsal system. The need for alternative systems which are better matched to the head/eye characteristics has led to the development of more radical solutions which are discussed below.

Head/Eye-Slaved Displays. For many military aircraft, and particularly for helicopters, the wide canopy allows the aircrew to view the outside world over a very wide arc, using a combination of head and eye movement. As the head and eyes are moved, the instantaneous field-of-view occupies only a small part of the total swept field-of-view, so that the remaining part cannot be seen. It follows that a fixed simulator display which covers the total field-of-view is always providing an image of which only a part can be seen at any instant. By moving the position of the displayed image in space so that it is always centered upon the eyes' centerlines, this waste of image can be averted and considerable image display and processing can be saved.

Slaving the display image to the eyes requires knowledge of eye pointing direction, and this is not easily measured. A simpler concept, which is easier to implement, is to measure head orientation and slave the display position to it; the display must then have a field-of-view equal to that of the eyes plus the maximum angular movement of the eyes within the head. A number of research and training simulators have used this technique [4.9, 4.10] and there are several suitable head position sensors commercially available. The display is usually of the projection type using a dome screen. An alternative and much simpler arrangement is to mount the display on the pilot's helmet so that it automatically follows the head movement, but helmet-mounted displays have disadvantages of limited field-of-view and resolution as well as being rather clumsy to wear.

It is likely that research into the techniques of measuring eye position will, in the near future, generate compact and accurate sensors that will enable the eyes' point of regard to be accurately determined. This will allow the so-called point-of-regard displays to be developed as practical simulator devices. In these displays advantage is taken of the eye resolution characteristics described in 4.1.1 and illustrated in Figure 4-2. The displayed image is configured to have a central high-definition area corresponding to the central high-resolution area of the eyes, together with a lower definition area for the remainder of the field-of-view. Significant saving in image processing results, but the transport delay in the processors, which is a problem with helmet-mounted displays [4.10], has to be reduced to prevent perceptible lags with rapid eye movements. As with head-slaved displays, point-of-regard displays will probably be mainly of the projection type with the complication that the central and outer areas must be blended together to prevent a perceptible boundary.

The main advantage of point-of-regard displays is that, by properly matching the display characteristics to those of the head and eyes, they are able to provide levels of resolution which should be adequate for the most demanding tasks. It can be expected that, as the techniques and equipment for measuring and display-rotation become further developed, these types of display will be increasingly used in training and rehearsal simulators [4.11].

Airborne Displays. In the discussion on airborne map displays in 2.5 it has already been noted that the small size of display space in military cockpits and the ambient light conditions seriously degrade the display quality to the extent that formats must be simplified. The situation for perspective displays is similar, and because of the complexity of some visual scenes may be even worse. It is, likely therefore, that display limitations will be a significant factor in determining the effectiveness of future airborne mission planning and rehearsal systems incorporating perspective displays. It is possible that helmet-mounted point-of-regard displays may have useful potential for airborne application, but much research on both the technology and on the human factors aspects will be required to establish their real value.

4.1.4 Sensor Displays.

Most modern military aircraft are equipped with imaging sensors which are used to aid the aircrew in such tasks as ground clearance and navigation, target detection, acquisition and recognition. For these purposes the sensor image is displayed to the crew on displays, usually CRT's, on the instrument panel or helmet-mounted. In providing a simulation of a planned mission for rehearsal purposes it is necessary to simulate the sensor displays with appropriate fidelity, particularly if this sensor information is critical to the success of the mission.

The display and the associated processing do not present a problem since these can be based on those used in the aircraft. The other elements of Figure 4-1, the database and image generator, will be similar to those used in a visual simulation, but may have the following significant differences:

1) The resolution may be either greater or less depending upon the effective magnification and field-of-view of the sensor.
2) Reflection characteristics at radar wavelengths of both terrain and features, and emission characteristics in the IR, will differ from those in the visual band and will need to be included in the database model. Speckle and glint are particularly difficult to model.
3) Atmospheric and ambient lighting effects may need to be included which are often quite different from those used in the visual model.

Training simulators have been built in which these differences have been successfully allowed for, and the techniques used should be equally applicable to mission rehearsal simulators. It should be noted, however, that the additional contents of the terrain and feature database models, such as glint information, may require more preparation time unless they can be generated by an automated process.

One problem reported in [4.12] concerns the need to ensure that the visual and sensor displays are properly correlated in terms of spatial content and of timing; this problem is particularly difficult when the image generators and databases for the visual and sensor images are developed by different organizations. Ref. [4.13] discusses the database requirements for the simulation of helmet-mounted night vision goggles which have spatial and intensity characteristics which require unique database shadow and contrast features.

4.1.5 Recommendations for Future R&D.

4.1.5.1 Map Displays.

Present trends are increasingly to use equipment based on commercial standards for the display of map information in ground-based mission planning systems; this has significant advantages in terms of first cost, updating and modification cost and Interoperability. It is unlikely that future system requirements will result in any departure from that trend. Future systems will take advantage of improvements in commercially-available technology as they appear, but it appears unlikely that any R&D aimed specifically at the military map display application will be required.

For airborne map display, where present displays are clearly inadequate for mission planning purposes, research programs in many countries over several years are now beginning to produce flat-panel displays which are of sufficient quality to match CRTs. These programs will certainly continue, to meet the needs of both the airborne display market as well as a range of other commercial and military users, and it is likely the flat-panels will replace CRT's for most future aircraft. Airborne mission planning systems will be able to take advantage of future performance improvements, but no specific R&D is perceived to be justified.

4.1.5.2 Mission Rehearsal Displays.

There is currently very little experience of the usefulness of mission rehearsal systems, either airborne or pre-flight, and although the discussion in Section 4.1.3 has pointed to the need for improved display systems there is no experimental or practical evidence to substantiate this view. In recommending future R&D programs, it is therefore necessary to emphasize that the first need is to carry out properly structured experiments to establish relationships between the effectiveness of mission planning systems and the quality of the displayed visual scene. Experience of the development of training simulators shows that such experiments will be difficult to conduct, and that it will be many years before definitive information is available on suitable standards for display parameters such as resolution, field-of-view etc.

In the absence of this information it appears reasonable that improvements in display resolution will continue to be sought. The most promising way to achieve this appears to be by using eye point-of-regard displays as discussed in 4.1.3.5., and research in this area, which includes development of suitable eye-position sensors, is recommended. Such displays must be matched by image generators with low transport delays, but it can be expected that future image generators will be able to take advantage of the continuing improvements in computer power which will become available in the future.

Another desirable improvement, particularly in perspective displays, would be increased display brightness. Current CRT's are approaching fundamental limits, but liquid crystal displays having back-lighting or projection capability offer considerable promise in this respect, and development of versions optimized for simulation applications should be worthwhile. Provision of stereoscopic information could be useful for operation close to ground features, e.g. for helicopters, but more research is required to establish whether this would be a significant improvement. If it is, then it would be reasonably easy to incorporate into eye point-of-regard displays.

Two aspects of database design merit improvement. For mission rehearsal systems the time taken to build databases will always be a critical factor, and automation of this process to reduce time and manpower requires more R&D. The time and cost of building database models is also dependent on the availability of existing data in a form suitable for rapid and automatic reformatting as required. Initiatives such as USAF Project 2851 on standard formats for simulator databases should therefore be therefore be continued, preferably on a pan-NATO basis. The standardization of the formats used for other data, such as intelligence information, also deserves study.

4.2 ADVANCED INTERFACE TECHNIQUES FOR MISSION PLANNING.

4.2.1 Introduction.

The power of current state-of-the-art computationally-based systems is staggering. The evolutionary trend in the development of these systems indicates more power, through faster devices and more parallel processing, will be available in the future. These systems will be employed in future mission planning/mission rehearsal systems. The management of this power by the user, for mission planning or other applications, is largely constrained by the interface between the user and the system, where, in mission planning operations, the system can range from small field-operated units to shipboard mission rehearsal/planning units, and the user can range from a fighter pilot to a theater battle planner. A melding, through the interface, between user and system, can couple the inductive capability of the system with the enormous deductive power of the human user. Advanced multi-sensorial interface concepts and technologies can aid this melding process by providing a flexible and adaptive interface medium. This Section describes some of the advanced interface concepts and technologies which may be employed in future mission planning/rehearsal systems as well as begin to describe application of these concepts and technologies.

4.2.2 Virtual Interface Concepts.

The application of advanced, multi-sensor interface concepts may best be accomplished using a combination of non-virtual (or conventional) and virtual control and display devices. The use of a combination of virtual and non-virtual devices can create a novel experience for the user, an experience that, for mission planning systems, makes the mission planning task more of a mission rehearsal or mission training aid. This type of experience, in the general sense, has been termed virtual reality in the current literature. The perceptual space created by this experience has been termed the virtual environment.

The virtual environment concept takes advantage of the fact that humans experience reality through the combination of their senses and internal representations of the environment existing previous to the current sensory stimulation. The representation of a current environment developed by a human is formed by the continual processing of energy within the environment transformed by the human through the sense organs and transmitted within the human by the central nervous system. The processing of this energy within the human is complex and adaptive. Virtual environments can create artificial realities for humans. In essence, to the human in the virtual environment, one reality exists outside the virtual environment and a second reality exists within the virtual environment.

The display and control system which produces the multi-sensory stimulation for the user is generically called the virtual environment generator. A generic virtual environment generator can best be described by drawing an analogy with a computer graphics system. In fact, the traditional elements comprising a graphics system also comprise a virtual visual environment system. There is an image generator, an image transducer, a display, and finally an input, or control, mechanism. The difference between a virtual visual environment generator and a conventional visual environment generator is in the display itself; in the virtual visual case, the display is a virtual display. Examples of virtual displays are helmet mounted displays and head-up displays. Environment generators for the other human senses are comprised of similar functional blocks, with the display, transducer, and control taking a different form. Typically, the image generator, whatever the sense modality, creates the initial image electronically, the transducer transforms the electronic image into a format useful for the display, which creates energy which can be sensed directly by the human, such as light, sound, etc.

The quality of the artificial reality experience created by the virtual environment generator is dependent on the fidelity of the sensory stimulation. If the intent is to emulate a naturally occurring environment, the virtual environment must accurately recreate the sensory stimulus of the naturally occurring environment and accurately present it to the human observer, and allow the human to naturally interact with, and affect, the outside environment.

4.2.3 Enabling Technologies.

Several technologies are currently being utilized to create virtual environments. Some of these technologies are very mature, others are in their infancy. One of the most mature technologies is computer graphics. This is fortunate in that some estimates of information processing by humans list vision as typically being used for 80% of information input. This fact makes computer graphics the single most important technology for the creation of robust virtual environments.

Other technologies are also involved in the formation of visual environments. Some of these technologies are being considered for incorporation, or are already integrated, into aircraft cockpits. These include helmet mounted displays, helmet mounted head, hand, and eye line-of-sight trackers, and three dimensional auditory displays.

These devices have been, and continue to be, developed and evaluated by several academic, industrial, and military institutions. Other devices which enable the portrayal of virtual information are less further developed. These include tactile/haptic stimulation devices, hand and body flexure measurement devices, direct vestibular stimulators, direct retinal displays, and directly-coupled brain-actuated control.

4.2.4 Research Considerations.

The integration of virtual display and control techniques with conventional display and control techniques for mission planning systems should be guided by characteristics of the human interacting with the virtual environment. The human is a complex and adaptive receiver whose perceptual performance is tied to the quality of the visual and auditory stimulus generated and controlled by the display generators. Perceptual research which may impact the design, development and application of virtual environment technology in the areas of vision, audition, and proprioception is being pursued internationally. However, many questions remain unanswered regarding virtual techniques, which, when answered, may increase the potential usefulness of virtual interface. In addition, each new application of virtual devices brings new research questions to light. Some of the research questions are discussed below.

4.2.4.1 Multi-Sensory Integration Issues.

An area of research demanding significant attention at this time is the sensory integration aspects of displaying virtual information. While technology components for virtual displays have been developed, a complete understanding of the integration techniques required to blend these components into robust artificial realities does not exist. The need for an understanding of human sensory integration characteristics and display integration techniques is partially a result of the traditional boundaries established between researchers. In addition, a researcher in the area of sensory integration must posses a deep understanding of the characteristics of each sensory channel when operated independently. This is indeed a challenge.

The perspective to be taken in this research is one of viewing the visual-auditory motion perceptual interaction as a product of an integrated sensory/perceptual process. Humans are continually processing stimuli from multiple sensory sources and integrating these stimuli into coherent perceptions of their environment. The integrated perspective taken in this research enables the interactions and influences of the auditory and visual modalities to be illuminated and investigated.

Stroboscopic stimuli are significant within virtual interfaces. All visual graphics utilize stroboscopic stimuli as they redraw the visual scene in a raster format in discrete time periods and, thus, rely on apparent motion perception of the viewer to fuse the discrete images. Auditory virtual displays may be continuously excited or they may update the auditory presentation in discrete time periods in a similar fashion to visual displays. It is important that latency differences between the different sensory channels are not apparent to the human operator.

4.2.4.2 Augmentation vs Full Immersion.

When the use of virtual environments is considered for mission planning systems, the question of how much virtual reality is enough must be considered. Within the current virtual reality literature, this question is discussed using the terms full immersion virtual reality and virtually-augmented reality. A very good example in the aerospace field of virtually-augmented reality is the super-position of HUD symbology on out-of-the-cockpit features in aircraft. This, of course, has been done for many years and thus the term, virtually-augmented reality is a new term for an existing technique. Full immersion virtual reality is also not new, an example being flight simulation. The robustness of the reality created is at the heart of the question. While the pilot operating in a flight simulator is full-immersed, some of the cues found in the "real" situation cannot be fully duplicated in the simulator, such as acceleration cues. The extent of virtual environment use for mission planning requires to be explored in much greater depth than has so far been attempted.

Chapter 5
Computational Techniques

5.1 INTRODUCTION.

A major concern involving all aspects of mission planning systems is the tremendous computational burden that is required for a wide variety of mission planning functions. In this Chapter we address computational techniques for automating the generation of the mission plan. Presently, mission planning system software is used to support the mission planner in generating a plan, and to possibly assist in the evaluation of that plan. In the future, it is expected that mission planning systems will expand these functions to include automatic plan generation. In this mode of operation, the planner can enter mission constraints and objectives into the system and ask the mission planning system to generate the best plan it can, while meeting the objectives and constraints. The user can accept, reject or modify the resulting plan. However, in order to realize this capability, advances in computational techniques are required to deal with the severe complexity of mission planning problems.

Mission and trajectory planning problems are complex and difficult for a variety of reasons. First, multiple (and often conflicting) objectives must be pursued in the face of a variety of both implicit and explicit constraints. Representative mission objectives include reconnaissance, resupply, support and strike. *Implicit constraints* are constraints that are imposed by the vehicle design (e.g., its fuel carrying capacity, stores carrying capacity, performance envelope and subsystem capabilities). *Explicit constraints* are constraints that may be imposed by a higher planning authority (e.g., a required probability of survival or mission success, time or ordering constraints that may be imposed on the pursuit of specific mission objectives, navigation constraints, maneuvering constraints within the vehicle's performance envelope and constraints imposed by the time available to plan).

5.2 APPROACHES.

Computational techniques for solving mission planning optimization problems can generally be grouped into two categories:

- Optimal Approaches
- Heuristic Approaches

Optimal approaches have an advantage over heuristic approaches in that they are guaranteed to generate optimal solutions; however this performance advantage comes at the cost of much greater computational requirements for all but the least challenging problems. There are five classes of methods for generating optimal solutions to mission planning problems:

- *Complete Enumeration*. The simplest method of obtaining an optimal solution to mission planning problems is to evaluate every possible mission plan, keeping track of the best solution. This approach is, of course, completely impractical for all but the smallest problems as the solution time grows exponentially with problem size.
- *Dynamic Programming*. This approach generates optimal solutions faster than exhaustive enumeration. However, the solution times required by dynamic programming [5.1, 5.2] still grows exponentially (albeit less quickly than complete enumeration) with problem size.
- *Integer Programming*. As with dynamic programming, integer programming [5.3] approaches generate optimal solutions faster than using complete enumeration, but the time to solution still grows exponentially with problem size.
- *Gradient Methods*. Gradient methods [5.4] are useful for solving optimization problems that have well behaved utility functions. Gradient approaches have particular difficulty for utility functions that contain large numbers of local maxima (which is the case for the Mission Planning Problem) as they tend to converge on and become trapped in the local maxima.
- *Newton Methods*. Newton methods [5.4] use second derivatives (or the Hessian matrix for multi-variable functions) to improve upon gradient methods. These approaches are useful for certain types of optimization problems that have well defined utility functions, but are otherwise difficult or in some cases impossible to use, as is the case for the Mission Planning Problem.

The major hope for applying optimal methods to mission planning problems is the development of parallel processing architectures. Parallel processing architectures are reviewed in Section 5.2.

In addition to optimal techniques, there are a variety of sub-optimal, heuristic approaches, available for solving large scale optimization problems . The following methods were identified as methods that might be applied to mission planning systems.

- Machine Learning
- Expert Systems
- Neural Networks
- Simulated Annealing

In Section 5.3 we review these heuristic methods and discuss their possible applications to mission planning problems.

5.3 PARALLEL PROCESSING.

To make the use of optimal methods in solving all but the most rudimentary mission planning problems, it becomes necessary to look to parallel processing architectures.

5.3.1 Hardware.

The spectrum of approaches to parallel processing can be classified in terms of a few fundamental characteristics: granularity, i.e. the size and capability of the individual processors; The processor architecture, (i.e. the way in which the processors and memory elements are interconnected); and control, (i.e. whether system behavior is directed centrally or in a distributed manner). A parallel processing solution to a given problem should incorporate the combination of these characteristics that best address the computational aspects of the problem. The Strategic Computing Initiative (SCI) is currently funding a variety of hardware realizations of parallel processing concepts that represent promising candidates for the spectrum of intelligent system applications that DARPA envisions.

The specific parallel processor systems supported by the SCI include the Systolic Array, the Butterfly Machine, NON-VON, DADO, Dataflow Machines and the Connection Machine [5.5]. Others may emerge as a result of current architecture competitions [5.6]. In addition, other parallel processing architectures have been developed outside the scope of the SCI, such as the Delencor HEP.

Although much work has been done in the hardware development of parallel processors, the applications of these processors is still in its infancy. Applications such as solving linear equations or singular value decompositions on systolic arrays have been successful, but a significant application of these machines in real-time decision-making environments has not been accomplished. In particular, solving unstructured problems like the planning problem described in Chapter 2 has not been attempted. With the present maturity of planning algorithms and related areas of artificial intelligence, the time appears ripe to exploit these architectures.

Parallel machine architectures may be broken down according to a number of different criteria. An important major classification is computational granularity, the processing power of the individual computing elements contained within the architecture. As a practical and economic matter, the smaller the granularity, the larger the number of computational elements that may be interconnected. Therefore the most massively parallel machines are always constructed from the simplest of computational elements. One example of a very fine-grained parallel processor is TMI's Connection Machine, where as many as 65,536 individual elements can be interconnected to form a single parallel computing architecture. On the other end of the scale, a parallel processor may be built with very sophisticated computing elements, such as any of the advanced general purpose CPU's currently available. An example is the Encore Multimax multi-processor, which allows up to 20 National Semiconductor 32032 CPU's to be interconnected.

5.3.2 Applications to Mission Planning.

The field of mission planning provides numerous areas where speeding up computational performance would be beneficial. These areas include:

- Route Planning
- Radar terrain masking computations.
- Processing imagery.
- Providing 3D out-the-cockpit displays
- Data Fusion
- Database Management

It remains to be seen if the emerging parallel processing architectures can be successfully exploited by users. A major difficulty is developing application software that can effectively utilize the full potential of parallel architectures. To date, the most effective use of parallel processing has been in the image processing community. It is therfore expected that advances in parallel processing archititures will benefit mission planning system user interface technology and mission rehearsal technology. In other areas, such as route optimaztion, advances need to be made in software that is developed specifically to exploit parallel processing architectures. Some work is taking place in the academic community [5.7, 5.8], but much more work is needed to transition this research into the field.

The use of parallel processing architectures may prove to be most useful in supporting the mission planning process in-flight, where speed is much more critical then during the pre-mission planning phase. The development of flight-computers employing parallel processing architectures will be very important to the process of transitioning automated mission planning from pre-mission to in-flight.

5.4 HEURISTIC METHODS.

The use of heuristics to solve otherwise intractable combinatorial optimization problems has become widespread in both the engineering and operations research communities. Heuristics are strategies, ideas, rules, guidelines, procedures, recipes, or methods used to guide a search toward the optimal solution within the solution space. Heuristics exploit knowledge about the specific problem domain to intelligently guide the search, so that near-optimal solutions can be generated in a fraction of the time that would be required to generate optimal solutions. Below we review some of the heuristic methods that may be applicable to mission planning problems.

5.4.1 Machine Learning.

Recently there have been significant advances in the area of machine learning algorithms that offer some promise to the area of mission planning. One such learning technique that has been applied to mission planning problems is associative reinforcement learning, which occurs when reinforcement is used to form associations between stimuli and responses. Although associative reinforcement learning has been a subject of research for many years, the difficulty of assigning credit for reinforcement to specific responses in complex learning situations has restricted its domain of application to simple learning problems of little practical importance. However, recent theoretical and experimental studies based on Klopf's model of associative reinforcement learning [5.9, 5.10] which deal with goal-seeking adaptive networks composed of goal-seeking adaptive components [5.11] suggest that it may be possible to extend associative reinforcement learning to more difficult learning problems whose solutions would have practical significance. The references cited above discuss these results and provide extensive references to other relevant research.

There is an important distinction to be made between reinforcement learning and error-correcting learning. In the case of error-correcting learning, the system need only remember what it is told (or be capable of generalizing therefrom). In the case of reinforcement learning, on the other hand, the system must discover what responses have consequences that lead to improved performance. A statistical adaptive procedure, wherein the chance occurrence of appropriate or inappropriate behavior is rewarded or punished, plays an important role in this process of discovery. Information from the environment is used to reward or punish the system's behavior, but does not instruct the system as to what the correct behavior would have been. This statistical adaptive procedure enables the reinforcement learning system to construct a model of the system and the environment without having to explicitly solve the difficult credit-assignment problem alluded to in the previous paragraph. As the model becomes more refined, the behavior of the vehicle becomes more directed and the statistical aspect of the adaptive process becomes less important. Reinforcement learning systems are thus able to improve their performance in environments that provide information that is of lower quality than would be required by error-correcting learning systems.

5.4.2 Expert Systems.

An expert system is a collection of rules, along with a procedure for using the rules to generate satisficing solutions to a wide spectrum of problems. The rules are generated by human experts in the problem domain; therefore expert systems are somewhat similar to heuristic methods. The primary difference between the two is one of implementation. Heuristic search techniques tend to be algorithmic, while expert systems are implemented using inference engines (e.g., forward or backward chaining) that operate on a rule base. Expert systems find solutions that are consistent with the rules, but do not necessarily search for optimum solutions.

Recent applications of expert systems technology to a large class of engineering problems [5.12 -5.20] suggest that expert systems may be useful for solving complex aerospace planning and control problems. Indeed, major efforts are underway to develop expert systems for a wide variety of aerospace applications including DARPA's Pilot's Associate program [5.21], NASA's space station energy management system [5.22], and NASA's Systems Autonomy Development Program [5.23].

Some of the aerospace applications for which expert systems are currently being considered are closely associated with real-time life-critical operations. Thus, it is reasonable to expect that eventually such expert systems will play real-time, life-critical roles in these applications. As with other systems that perform life critical tasks, these expert systems will have to be thoroughly evaluated before they can be flight tested. This evaluation process is necessary to ensure that reliability and performance requirements are satisfied. However, a satisfactory and generally accepted methodology for evaluating the reliability and performance of expert systems does not currently exist.

Historically, because expert systems have not addressed life critical and/or real-time problems, there has not been a compelling need to address the evaluation problem. To date, most investigations of the evaluation problem have been either incomplete [5.24], strictly qualitative [5.25], [5.26], or problem specific [5.27 - 5.30]. Recently, NASA convened a workshop to address issues associated with verification and validation of knowledge based systems [5.31]. The lack of a general, complete and quantitative evaluation methodology is a major impediment to exploiting the potential of expert systems in aircraft and spacecraft systems.

5.4.3 Neural Networks.

The application of neural networks to the solution of optimization problems [5.32] appears to have a variety of interesting applications, among which is the solution of combinatorial optimization problems. In spite of its novel perspective, however, the Hopfield approach to the solution of these problems is limited by its inability to find global minima with a single invocation of the algorithm. It is effectively a steepest descent procedure that settles at the nearest local minimum. Global minima are achieved only by initializing the algorithm at a sufficient number of different starting points. The primary difficulties of using neural networks to solve optimization problems are: adapting the networks to solve constrained optimization problems; and mapping complex optimization problems into neural network representations.

The Boltzmann Machine [5.33], and the Stochastic Neural Network Machine [5.34] combine the parallel architecture of the Hopfield network with the optimal seeking property of Simulated Annealing (see 5.3.4). The Boltzmann Machine minimizes the same energy function that the Hopfield network does, but it does so in the stochastic manner of Simulated Annealing [5.35]. Increases in the energy of the network occur with a probability that is a function of a temperature schedule. In this manner, the Boltzmann Machine escapes local minima that may be encountered during the search for the global minimum. The Stochastic Neural Network Machine also minimizes the energy function of the Hopfield network in accordance with a similar system of differential equations. A white noise term is added to the dynamics of each neuron in the system to keep the solution from settling into local minima. The noise term is, once again, a function of a temperature schedule. Early in the solution procedure, the temperature is set high to allow escape from local minima, while later on, the temperature is reduced to allow convergence to the global minimum.

5.4.4 Simulated Annealing.

Simulated annealing, which was invented by Kirkpatrick et al. [5.36] is a probabilistic algorithm for solving large scale optimization problems with arbitrary cost functions. It is based on an analogy with the physical annealing process for glasses or metals, where low energy states in substances such as metal alloys are attained by first heating the substance, then cooling it slowly. This process allows the system to relax into a low energy configuration, without quenching, i.e., without getting trapped in higher energy states. Simulated annealing uses this approach to find the solution of large scale optimization problems.

By analogy with the physical annealing process, a parameter called the "temperature" is introduced in the optimization procedure. This temperature, which at the start is high, is decreased gradually. At a fixed temperature, a procedure such as the one developed by Metropolis et al. [5.37] is applied to generate a Gibbs probability distribution over the solutions of the optimization problem. This Gibbs distribution gives higher probabilities to solutions with low cost function values, where the value of the cost function is analogous to the energy in a physical annealing process. The Metropolis algorithm or any equivalent method such as the heat bath technique [5.34, 5.38] corresponds to a stochastic relaxation procedure, whereby starting from a given initial solution, a statistical equilibrium is gradually reached. This equilibrium is characterized by the Gibbs distribution corresponding to the temperature of operation.

Conceptually, simulated annealing requires the gradual lowering of the temperature in such a way that the artificial system associated with the optimization procedure remains close to statistical equilibrium. As the temperature tends to zero, the probabilities of the various solutions increase for those with lowest cost function values. However, the requirement that the system should always be close to statistical equilibrium implies that the cooling of the temperature be very gradual in critical temperature zones.

Theoretical results [5.39 - 5.41] on the convergence of the simulated annealing procedure to the optimal solution require logarithmic cooling schedules, which makes the procedure extremely slow. In practice, faster cooling schedules are employed. However, these faster schedules result in a quenching phenomenon where the system gets trapped in a local minimum. If premature quenching occurs, the simulated annealing procedure will fail to reach the globally optimal solution, and may yield an unsatisfactory one.

5.5 CONCLUSIONS.

The computational techniques discussed in this Section represent the initial steps in the development of more sophisticated automated mission planning computational methods. It is expected that in the future, the development of these types of computational techniques will take on increased importance, as he response time for mission planning is reduced. The success of these computational techniques will depend on how fast they can be made to run, while maintaining satisfactory levels of performance. To accomplish this goal, it is expected that parallel processing architectures will become necessary to meet throughput requirements of the computational methods.

Chapter 6
Information Management

The mission planning process is dependent on the availability of up to date data that is derived from different sources. The management of such information is vital if the planned mission is to be successful. The area of information management is therefore an area of concern.

6.1 DATA FUSION.

Fusion of data for mission planning systems is required to reduce the total amount of information, combining different information from various sources and eliminating inaccurate data. Mission planning requires the fusing of geographical information and data on enemy assets.

6.1.1 Fusion of Geographical Information.

Mission planning systems and navigation call for a growing volume of geographical information: altimetry, planimetry (Roads, Towns, Railways...), images, three dimensional models of targets, toponimy, radar images, etc.

Usually, this information is produced by a centralized geographical survey. This service uses specific techniques to collect and refresh all the information. In this case, the time needed for producing the geographical information is very long and the operation is sometimes difficult when it is not possible to go into the field to manage survey missions.

Then it is useful to have a mission planning system merging new information just before planning or during the flight.

6.1.1.1 Sources.

For this aim the sources of geographical data are mainly from airborne or satellite sensors.

Airborne Sensors. There are various airborne sensors: Airborne Radar, Side Looking Radar, Optical or Electro-optical equipment, visually marked points.

The data collection through these sensors have different impacts on the pilot's workload. The information, if not displayed in the cockpit, is either recorded or sent to a ground station by data link. In order to collect this information, the pilot must point the sensor in the direction of the target or fly a predetermined track, but doesn't need to interpret the images during the flight. This is less demanding than information displayed in the cockpit which requires the pilot's interpretation to carry out the mission. This information is issued from a ground mapping radar, a Forward Looking Infrared, a Laser designator pod, or visualization of surroundings through Head up Display.

Satellite Sensors. Two types of satellites cover most of the optical spectrum. One is civilian: (e.g. SPOT and LANDSAT), the other is military (e.g., KH 8, 9, 11, for the US, Helios for France). But these satellites have limitations due to the weather, the clouds, and light in the area of interest. For these reasons the use of radar sensors appears to be complementary and operationally more interesting.

Images of on-board Synthetic Aperture Radars are being experimented with to generate digital Terrain Models or to localize targets with encouraging results. With this kind of sensor the delay for obtaining usable data is shorter.

Other Sensors. Geographical data can be also extracted from other sources, such as paper maps, intelligence, ground surveying or Geodesic GPS outputs.

6.1.1.2 Fusion.

Geographic data fusion is different when executed during the flight or on the ground during mission planning.

In-Flight. During the flight, geographical data are available from the airborne database, can be collected with airborne sensors, or can be received through a data link from another aircraft or from the ground.

The airborne database is used for navigation and a rough positioning of the sensors, which are then used for a precise designation of the target (cross road, bridge...). Airborne databases and sensors are alternatively operated according to the situation and the pilot's choice. In that case fusion is not necessary, because only one kind of data is used at same time: generally the precision of the onboard sensor is better than the precision of the localization obtained by the aircraft localization and the geographical database.

If the localization of the geographic target is not in the onboard database, the pilot and the aircraft system can designate and locate the position of the target, in real time, with high precision. This information is incorporated into the on-board database for future use.

This localization may be sent to another aircraft or to the ground mission planning system for future use, by JITDS or MIDS data link. Afterwards, it is included in the onboard databases of other aircraft.

On the Ground. Mission planning is different., involving more complex procedures for merging geographical data. At first, a permanent database (altimetric, planimetric, toponymic and radiometric) is elaborated using available peacetime techniques: satellites images, maps, etc.

This permanent database is then completed with newly collected data coming from aircraft, satellites, RPVs or other sources. This operation creates several problems as it requires handling of data of different types, such as images, photographs, raw outputs, etc. Data can have different definitions or precisions, and can give contradictory information on the same feature. However, they need to be merged in a consistent database to be used for future missions. For example, altimetry can be extracted from optical sensors, planimetry can be elaborated from SLAR or any kind of airborne sensor.

The pilot's recollection of the mission is also useful for identifying more specific objects, giving a finer description of them or any other unknown information.

There are many benefits to geographical data fusion: it allows increased operational performance, enhanced spatial resolution, greater pilot confidence and reduced mission envionment ambiguity.

6.1.2 Fusion of Data on Enemy Assets.

6.1.2.1 Airborne Information Sources.

Embedded Databases. The database generated during the preflight mission planning stage contains four types of data:

- geographic and meteorological data,
- physical and tactical data about friendly assets,
- data on missions and tactics,
- data on enemy assets.

If mission replanning is to be carried out in flight, this database will have to be updated accordingly.

JTIDS. JTIDS is a digital information distribution system providing integrated communications, navigation and identification capabilities. JTIDS participants may be friendly aircraft well as ground based C^3 stations. The data exchanged via the JTIDS network would include:

- changes in the threat environment
- mission status of other friendly aircraft,
- target tracks detected by other friendly aircraft.

With respect to the in flight data fusion process, target track data received via JTIDS may be regarded as data returned by another sensor onboard the aircraft where the data fusion process takes place.

Infrared Sensors. Airborne infrared sensors include FLIR and IRST. FLIR systems use the temperature gradient of an object scene to produce TV-like images at night as well as during the day. The pilot uses his image interpretation skills to detect, recognize and identify targets of interest. This identification process might be automated by correlating the FLIR images with a bank of pre-stored target IR signatures. The pilot's intervention would then be only required to support or invalidate the decision reached by the correlation process.

IRST is used primarily for detection of hot spots in large volume searches and subsequent tracking of designated targets. In the tracking mode of operation, the IRST system can be locked onto a single target, tracking that target in angle or it can be used in a track-while-scan mode, where several targets are tracked by a computer and the IRST system remains in the search mode updating target angular positions periodically. In all cases, the outputs of the IRST are the target 2D tracks (angular position and angular velocity).

Visible Sensors. Visible imaging sensors require the pilot's intervention to analyze the displayed scene, especially to recognize and identify targets of interest. This scene analysis process is difficult to automate, since this automation involves pattern recognition techniques.

Electronic Support Measures (ESM). ESM involves:

- detecting enemy signal activity,
- classifying signals,
- calculating emitter locations,
- extracting intelligence from operational characteristics, signal technical characteristics or emitter location.

ESM outputs include angular location and indentification for each emitter.

Microwave Radar and Laser Radar Systems. Future microwave airborne radars will essentially be multi-function. Their operation is highly automated, the pilot's intervention possible but rarely necessary. In most modes the radar's outputs will consist of the target tracks. These tracks will be 2D (angular localization in a passive search mode for example) or 3D.

A signature analysis mode might also be available. In this mode, the radar performs an accurate measurement of the target, and the return is correlated with pre-stored target radar signatures.

Laser radar systems are active devices that operate similarly to microwave radar but at much higher frequencies (1.06mm for the Na-Yag laser and 10.6mm for the CO_2 laser). They can be used for accurate target localization or for identification.

They can be used either in a detection and tracking mode where they are capable of tracking with high resolution target designated by another less accurate sensor, or in an imaging mode where they can produce high resolution pictures of targets and areas of the ground.

6.1.2.2 Airborne Data Fusion.

The data fusion process establishes global tracks from those produced by the different sensors described previously.

The sensor tracks are combined periodically (at regular fusion time points) into global tracks. These global tracks can then be extrapolated forward in time and made available for use whenever an estimate of the environment based on all sensors information is required.

The organization below outlines how the sensor tracks are combined to provide global tracks:

- alignment: sensor data are transformed into a common space and time coordinate system,
- association: this process determines whether a global track and a sensor track represent the same target,
- updating: each global track is updated, via a track fusion algorithm, with the sensor track it has been associated with at the previous step.

6.1.2.3 Differences Between Ground-Based and In-Flight Mission Planning Systems

The main differences between ground based and in flight mission planning are that ground-based systems provide:

- Large choice of possible missions
- Large amount of data available
- Sensor data is not available
- Important response time is allowed
- Based on communications
- Data fusion process can be complex and difficult to automate

The system must be robust against any virus which could produce data anomalies or data destruction as well as against unfriendly information detection or unfriendly intrusion into software, especially during data loading.

6.5 POST-MISSION REVIEW.

During flight a lot of parameters are to be recorded to be used after the mission. We can quote:

- Recording related to the aircraft, the engine, and to the aircraft systems.
- Recording related to the weapons delivery and navigation systems.
- Recording related to enemy electromagnetic threat.

The goals of the first type of recording are to monitor the airframe fatigue, the engine, and to analyze failures, accidents or crashes. From the technical point of view the recordings are used for maintenance after failure, for general maintenance and for logistics.

The goals of the second and the third types are operational and technical. From the operational point of view the recordings are used to analyze mission results, to perform intelligence data exploitation analysis to complete the threat database. This information will be used for combat management and tactics employment and also for training.

For these aims there are four different sources of information. Video signals which include:

- landscape camera with Head Up Display receptacles
- head level display
- head down display

Audio signals which include:

- radio communication
- pilot's voice
- audio warnings

Digital data which include:

- aircraft parameters and trajectory
- self protection system parameters (threats parameters)
- data links communications

and photography and recce equipment. There are several means to bring these data down to the ground:

- the audio/video recording assembly
- the mass memory
- the data link

To decrease the pilot's workload it is useful to have an automatic recording of the most important events during the flight updating the data.

Chapter 7
Systems Evaluation

7.1 INTRODUCTION.

Aircraft, avionics systems, and support systems all undergo thorough developmental and operational test and evaluation phases. Developmental test phases allow for the evaluation of the system in controlled laboratory settings. These phases also provide avenues for constrained approximations to "real world" situations with carefully controlled parameters measured in uncontrolled or partially controlled settings (e.g., developmental flight testing). Developmental testing allows for an initial "shake down" of the system before it progresses in the acquisition cycle. Operational test periods follow and open the opportunity to warrant the system under the rigors of everyday use.

While other combat readiness systems have undergone strict test and evaluation phases as part of their acquisition processes, mission planning systems have not been needed to fulfill this requirement. Historically, mission planning system testing has been limited to independent validation and verification (IV&V) of the software. This IV&V often does not include a validation of the models driving the mission plan, no test of the hardware and no test of the operator interfaces or systems integration. Verification traditionally centers on the confirmation of the software, focusing on the faithfulness of the code to achieve the aim of the programmer and the ability of other programmers to follow the code written. The verification of the software is carried out by software engineers or test operators. Validation is the authentication of the mission planning system including output accuracy (performance envelopes, times, fuel expenditure) and sensibility (are the outputs sensible in terms of mission performance).

7.2 NECESSITY OF TEST.

The importance of test and evaluation of mission planning systems has largely been ignored because the end users (operational forces) need the systems. While other combat readiness systems are required to undergo extensive validation, verification, test and evaluation prior to deployment the operational need overcomes the requirement to investigate the mission planning system prior to acquisition. Most mission planning systems are put into service without any type of test or validation phase.

Mission planning testing and evaluation are necessary to affect a successful implementation of the system in the operational environment (reference 7.3). This test and evaluation is required at the research and development stages as well as the operational test and evaluation phase to allow for the continued improved performance of the system as well as improving operational mission accomplishment. Further absence of testing may occur since, initially, testing of mission planning systems appears impossible. Lack of acquisition requirements, poorly stated design requirements, and the pressing need to get good mission planning systems out to users overshadows the importance of a thorough definition of the parameters. Satisfactory metrics are therefore difficult to delineate because the topic area is not well defined or quantified.

Before the design of a new mission planning system (or the upgrade of an older one) begins systems architects ask questions to determine the system requirements and system objectives. Testers and evaluators have many more questions which may ultimately be more difficult to answer because they depend on satisfactorily stated answers to the designer's questions. These questions include performance definition, performance measures, definition of success, measures of success, definition of failures, failure metrics, part test versus whole test of the system, test scenarios generation and content (peacetime, potential escalation, wartime), operator interface, maintainability, and logistics, to name only a few.

7.3 METHODOLOGY.

7.3.1 Areas of Test.

Two areas of test to be followed include "pushing the envelope" (to determine where the system falls apart) and exploration of the potential of the system (to determine the capability in terms of the operational mission, utilizing realistic mission scenarios). Both types of analysis are meaningful since the data from each are relevant.

It is worthwhile to test mission planning systems in both of these fashions. The first (testing the operating envelope of the system) demonstrates all that the system can accomplish. Because it is not bound by operational constraints it is possible to explore the strengths and weaknesses of the software that might never be unveiled in the operational environment. This data is intriguing but of limited utility because they cannot be generalized to operational uses. The second test type (operationally driven, " real world" evaluation of the system) yields mission data that is oriented to the types of questions operators ask. The evaluator must be careful about the design of the mission scenario used for test. These scenarios must be realistic and operationally oriented. Further, they must cover a wide range of the possible missions available. Additionally, these scenarios must cover all the features of the new mission planning system that make it superior to the old systems. In that way the comparison stems from the differences between the mission planning systems rather than the different scenarios. The evaluator therefore has constrained some of the parameters and examined the differences in the plans. These differences will highlight the differences in the mission planning systems themselves. This data is generalizable since it is a comparison of data sets generated by known mission planning systems. Unfortunately this qualitative comparison is currently the only data available.

7.3.2 Current Testing Approaches.

As stated above, testing currently revolves around independent validation and verification of the software. In some cases this does not cover the verification of the algorithms, only the capacity of the program to function without runtime errors. Nothing to date has addressed the robustness of the mission planner. A mission planner is robust if it yields a successful plan in spite of an incomplete database [Ref 7.1]. How successful the plan must be has not been quantified. It is important to note, particularly in a hierarchically ordered modular system (such as most mission planning systems), that the levels of the system must be evaluated and further, the system as a whole must be tested.

With the increasing complexity of mission planning systems, the concomitant expansion in diversity of architecture of the systems (with the use of more modular systems), and the escalating need for better integration of the mission planning system into the combat readiness systems (aircraft, surface forces and ground forces) (reference 7.2) it is becoming more critical to test at both the molecular level (subsystems) and the molar level (entire system).

Modular architecture's advantages include ready upgrading with minimal hardware cost. Further, the subsections help to reduce the obsolescence of the system by only requiring partial hardware upgrades or retrofits (reference 7.1). The increased modularity would work well with the advanced avionics architectures currently in design and test as these architectures are also modular and are designed for interface with other modular systems.

Molecular testing is especially suited to a modular architecture, allowing for control of the inputs and outputs at the various levels of the system. Since mission planning systems are used at many levels (at the levels of the individual aircraft, the group, the squadron, the unit, the theater) the tests must reflect that diversity of purpose. There are no discrete events in a hierarchical system. A change made at one level of the hierarchy will have trickle down and trickle up effects at each other level of the system. That same change implemented at another level of the hierarchy will result in different consequences at other stages. Additionally, any change made at one level will have different effects at levels above it in the hierarchy than at levels below it. Therefore any test must explore these hierarchically driven differences and evaluate the significance of those changes on the outcomes at other levels.

7.3.3 Other Evaluations.

At a more "nuts and bolts" level the relative importance of such details as hardware, software, and the human computer interface have to be determined and evaluated. These tests are comparably easier to sketch out since the specifications for these aspects of the systems exist to detail the design and function. Here again it is important to test the parts of the system as well as the system in its entirety. The current common systems approach to testing indicates that the reasonable method would focus on the software, the hardware and the human computer interface simultaneously. In this fashion it is possible to see the system working as a cohesive whole rather than as a collection of modules.

7.4 PROBLEMS.

There are a large number of potential problems with test and evaluation of mission planning systems. The first is putting forth the requirement for testing. Perhaps the most immense problems are related to the indeterminate vocabulary which engenders undefined testing programs. The definitions of parameters and measures of success are ambiguous and/or nonexistent. Without these definitions it will continue to be impossible to successfully evaluate any system. Some of the parameters that require definition include acceptable probability of success, probability of kills, logistical values (acceptable fuel expended, munitions utilized, system failures, mean time between failure), acceptable reroutes in flight (will reroutes be acceptable in-flight or will all planning of necessity be ground based?), alternatives (should targets become unavailable due to previous successful missions, inappropriate intelligence, or unforeseen problems en route). Further performance measures should include reduced mission planning time, operator satisfaction with the output, and systems integration with other systems in the platform.

Portions of this ambiguity are driven by the diversity of missions, options, and strategies to be addressed by mission planning systems. This returns us to the messy analyses that arise from having unbounded parameter sets. The modular architecture further clouds the issue as test results at one level do not reflect outcomes of the same test at other levels.

There is a requirement to improve mission planning system test and evaluation. It is evident that the current plans for evaluation of these systems are inadequate. Future testing must focus on the definitions of parameters and the mission relation of all test articles so that the data are both interesting and useful to the evaluators, and ultimately, the users.

7.5 POTENTIAL AREAS FOR R&D.

As the modularity and hierarchy of the systems increase the complexity of the testing required may appear daunting. The number of potential options yield impossible designs that cannot be easily comprehended or easily analyzed. Fortunately the same technologies that drive the increasing complexity of the mission planning systems have also touched the testing area.

There are a number of potential test and evaluation tools including intelligent testing and mission simulation. These instruments could allow evaluators a better view of the mission planning system by forcing the definition of requirements and measures. Further, they allow for more broad reaching data collection as they are inexpensive and effective.

Some basic tenets of testing hold true regardless of the improved performance of the technology. Controlled experimental designs are helpful in determining cause and effect relationships in data as well as helping to establish interactions evidenced in the outcomes. These types of designs do not lend themselves to most operational test and evaluation situations simply because the number of parameters is very large and the number of levels of each parameter may be infinite. Modified methodological designs can be used but even these are difficult to fit into most operationally determined tests.

7.5.1 Intelligent Testing.

Intelligent testing is a procedure in which an expert system is used to design an experiment that takes into account all aspects of each variable. The expert system is given all the rules and models with which to work. Because the experiment is a simulation of all the variables but without a man-in-the-loop, it is possible to collect data on all combinations of parameters without exorbitant cost. By mapping out all the simulation data over time a surface is generated. Sharp peaks and valleys on the surface indicate areas of interest that can be explored via more expensive laboratory and/or field testing.

Intelligent testing allows the user to test all possible combinations of the parameters, while conserving funding. The outcome then illustrates to the investigator the areas of interest that should be explored more thoroughly through man-in-the-loop simulation and later in more traditional methodologies.

7.5.2 Mission Simulation.

Man-in-the-loop simulation allows for test of a large number of parameters. Usefulness of the output may be the most telling qualification of a mission planner if an appropriate measure is determined and utilized. Man-in-the-loop simulation is a useful and acceptable methodology in research, test, and evaluation because it allows a large number of parameters to be tested in a restricted test space in a highly controlled experiment. Collecting data from a controlled experimental methodology allows for collection of vital data that are difficult or impossible to collect in operational settings (in-flight or underway). For systems such as mission planners, man-in-the-loop simulation allows for more expedient, less expensive test of the output plan covering more varied missions. Further, this method allows for safe data collection and gets the operator into the loop. At this stage of testing the operator inputs can be meaningfully incorporated into evaluation of the system.

The combination of intelligent testing and mission simulation allows for efficient, cost effective test of the entire system. The data from these tests allow the evaluators to structure the experiments conducted in developmental test phases and in the operational test phase so that the most useful information is gathered in the most productive manner.

Chapter 8
Conclusions

8.1 INTRODUCTION.

This report covers the Phase Two activities of the Working Group during which the preliminary findings of Phase One were explored in greater depth. The Phase Two studies have not resulted in a well-defined path for the development of mission planning systems, but rather a whole range of possibilities has been identified from which systems to meet particular requirements can be developed.

The following sections summarize the most outstanding conclusions of the Working Group. These conclusions are structured according to mission stage: pre-flight, in-flight or post-flight. Conclusions on pre-flight applications include mission planning, mission rehearsal and training (Sections 8.2.1. and 8.2.2). Mission planning support in-flight includes various crew assisting activities (Section 8.3). Post-flight use of mission planning systems is equivalent to mission evaluation providing input for subsequent missions (Section 8.4).

Sections 8.2 to 8.4 distinguish various applications of mission planning systems: preflight (planning, training, rehearsal), inflight, and post-flight; there should be a generic concept that integrates these applications in one concept.

8.2 PRE-FLIGHT.

8.2.1 Mission Planning.

Pre-flight planning tasks have been investigated and described since the 70's, and led to the development of numerous pre-flight planning systems. A variety of automated tools for pre-flight mission planning is already being developed or operational. Anacapa Sciences conducted a review of the relevant literature compiling a comprehensive list of specific information that must be considered during mission planning. The NAFAG distributed a questionnaire to collect data on the status of mission planning aystems. Conclusions of these enquiries that proved relevant to this Working Group are summarized in Section 1.2.1.

Joint Working Group 15 has not compared existing mission planning systems in greater detail, as that was considered of limited additional benefit at the cost of an extensive amount of additional effort.

Mission planning systems differ widely in capabilities. This is due to the lack of a unique definition or specification of capabilities that constitute a mission planning system. Most literature on mission planning systems addresses only the computational approaches of route planning (fuel consumption, attrition risks); this represents only part of the mission planning process.

The changed military scene may require some additional capabilities to the present mission planning systems:

- future conflicts may arise in areas for which the available databases may be inadequate for mission planning, hence needing a rapid update. Such updates may be by satellite, aerial reconnaissance, or a fusion of these and other data. Such a requirement has been specified for the SOF MPS.
- interoperability experiences in "Desert Storm" have not been encouraging (see Section 1.2.2). There is a growing importance of interoperability in mission planning systems between force types, nations, command and control levels, and platform types.

Existing pre-flight mission planning systems have reached a stage of maturity at which it seems unrealistic to expect that interoperability issues can be resolved with systems of the present generation; agreements on a high level architecture of components of mission planning systems and their interfaces (pre-flight or in-flight) should facilitate the exchange of components and should enable concentration on the development of isolated components.

Introduction of greater computational capabilities is expected to allow greater emphasis on areas such as data fusion and battlefield prediction (Chapter 6).

8.2.2 Mission Rehearsal and Training.

Contrary to preparing for a conflict between NATO and Warsaw Pact forces in Europe, it may not be possible to train and rehearse in regions of future conflicts (section 1.2.2). The operational environment may not be defined, it may not be possible to train in a comparable environment. This lack of an environment for operational training indicates the growing importance of systems for rehearsal.

Experiences with mission rehearsal for "Desert Storm" have been encouraging (see Section 1.2.2). For future procurement, mission rehearsal trainers have to be able to be reconfigured quickly from one aircraft to another and be as deployable as the forces themselves (see Section 3.6). Aircraft carriers are one means of transporting and hosting both these forces and their deployable mission planning systems. The capability for pre-flight mission rehearsal is expected to become more available as the machine capabilities increase. This is seen as a major factor increasing mission effectiveness. If "rehearsal" is for a non-specific task, then this is normally regarded as training.

8.3 IN-FLIGHT.

Prior to concluding in-flight planning, it should be clear which tasks are part of mission planning and which are part of tactics that may be trained or rehearsed, see Section 8.2.2. Rerouting as a consequence of threat avoidance may be considered tactics instead of an in-flight replanning activity.

In-flight mission planning resembles pre-flight planning but is performed while a pilot is performing other tasks that may be more important. Time constraints and pilot workload require a management capability that assigns priorities to tasks. A previous AGARD working group (WG 7, [1.6]) has already addressed this subject.

The Phase One report (Chapter 4) has pointed out the difficulties of in-flight planning. The majority of the problems are in communication, coordination, and identification:

- communication requires a secure, unjammable data link

- Close Air Support missions require coordination with the army , air defense missions have to be coordinated with other units (surface-to-air defense systems, other controlling agencies)

- before attacking it, identification of a target always has been important, but nowadays the effective range of (stand-off) weapons is too great to identify the target visually. Identification is especially delicate in CAS missions because the ground troops are in a contact situation. Hence the requirement for up-to-date intelligence data to be available to the pilot.

Deconfliction and target assignment in air-to-air and Close Air Support missions are mission planning functions that cannot be planned preflight (e.g., Phase One report). As a consequence, these mission types are only partially supported by present preflight mission planning systems (except for the route planning function, see Chapter 1). "Desert Storm" has demonstrated that in-flight updating of databases under certain circumstances is a reliable concept for air-to-ground missions (section 1.2.2), and future technologies may allow a shift of tasks from the tasking agency, the interceptor controller and the ground liaison officer to the crew in the mission aircraft.

In-flight planning may be carried out by:

- the aircrew

- a planning team, in another aircraft (e.g., other aircraft of the flight or an AWACS)

- a planning team on the ground (e.g., a fighter controller in a bunker or a forward air controller in the battlefield). If the planner is in an ABCCC/AWACS/JSTARS aircraft the MPS may have the same capabilities as a ground based system.

The current state-of-the-art of in-flight planning is limited to re-planning a mission by using options that have already been planned pre-flight; examples are the attacking of alternative targets, execution of system failure procedures.

As far as the interface is concerned for in-flight MPS, it must be pointed out that it is not conceivable in tactical aircraft to have a dedicated interface, but the same multi-function displays and controls used for other mission tasks shall be used for mission planning (see Chapter 4). In addition, a commonality in formats and symbologies should be pursued. It is likely that in most cases the mission planning task will not be the sizing factor in cockpit design, rather, the available cockpit lay-out will strongly influence the pilot / MPS interaction capabilities.

So, the in-flight MPS shall cope with the following additional constraints:

- minimize pilot attention and workload requirements

- avoid interference with other primary mission tasks

- be sufficiently reliable in its automated functions to gain complete pilot acceptance

- communicate with the pilot through physical and logical interfaces designed primarily for other tasks (except for particular cases).

If the mission planner is the aircraft crew, it could be useful to have a commonality in interface and function, both on board and on the ground. If this system is to be used for other aircraft types as well, however, this may result in interoperability difficulties due to the existing differences between interfaces and functions in different aircraft types (see Section 1.2.3).

So a dichotomy can be foreseen between the interoperability requirements and the integration of such systems with the entire system. In fact, future aircraft will not include a physically distinct mission planning system, but a mission planning function within the overall integrated avionics system.

In ongoing programs, in-flight mission planning is not regarded as a separate subject, but is integrated in covering crew-assistant programs (PA, CE, MMA (see section 1.3.2)); mission planning in these programs is an important function within the overall system. Although these ongoing crew-assistant programs seem a good starting point for future developments, their different architectures may hinder future joint production of crew assistant systems. Such a joint production may be a must in order to reduce development costs and to meet NATO's future force structure concept; in this new concept small force units of various nations should cooperate at squadron level, making interoperability an even more important aspect. The basis of such a joint production is a common concept of crew assistant functions, which could be defined on the basis of commonalities in the architectures of PA, CE and MMA.

8.4 POST-FLIGHT.

The capabilities of the post-flight functions of mission planning systems as described in Section 6.5 are expected to increase. The increasing amounts of data collected and recorded during a mission will need to be fed into the C^3I network rapidly to ensure that further missions are planned on the basis of up-to-date information. This may require improved brief and debrief facilities as well as mission rehearsal capabilities.

8.5 EPILOGUE.

In the Phase One report is was stated that "mission planning doctrine and technology has lagged far behind many of the aircraft technology developments since World War II". There are indications that this situation is changing, and there are now strong pointers to a more realistic appreciation of the value of advanced mission planning systems and their inclusion in programs like Copilote Electronique, Pilot's Associate, Mission Management Aid. Of the many possible reasons for this, it is likely that the most important is a re-appraisal of military needs following the collapse of the Warsaw Pact forces and the experience of Operation "Desert Storm". Also important is the fact that appropriate hardware and software are now commercially available at relatively low cost. Also, as resources are reduced, efficient mission planning is regarded as a force multiplier.

The rapid developments in computer hardware and software, together with parallel developments of their associated peripherals such as displays, have been generated by strong commercial pressures in a very large spectrum of civil markets and, although this may not continue at its present rate indefinitely, it can be predicted that in these technical areas there will be sufficient future progress to meet foreseeable needs of most military mission planning system designers at much lower costs than would be possible using technology designed specifically for the very narrow market of mission planning systems. An important task for further research and development must therefore consider the possibility of adapting this improved technology to the particular needs of military mission planning. Topics which appear to be of primary importance are

- overall system analysis, including detailed study of the tasks to be carried out by man and machine (Chapter 3)
- performance specification, which will permit proper test and evaluation (Chapter 7)
- proper analysis of the benefits of mission rehearsal, either through the use of a mission planning system having this inherent capability or by the use of a separate, specific mission rehearsal system (Chapter 1)
- cost / benefit studies to allow proper choice between the wide range of alternative performance levels which will become available.

The types of analytical study listed above, particularly those involving measurements of human performance in operational conditions, are inherently difficult. The situation has as its parallel the need for research on the value of training simulators: this has generally been carried out in an empirical and evolutionary way rather than by systematic analysis.

Finally, mention must be made of the topic of interoperability, a problem highlighted in "Desert Storm" (see Section 1.2.2). Because this was a subject studied by NAFAG, the Working Group has not given it the attention which it would otherwise deserve. But it has to be clearly understood that it presents a major difficulty, primarily because mission planning systems will almost certainly have features which are specific to the avionics equipment fitted to particular types of aircraft. As avionics becomes more complex, and more "intelligence" is incorporated, the need will increase for properly matched intelligence in each mission planning system, creating problems in attaining interoperability. Modern computer systems may make it possible to combine specificity with interoperability, but the combination of these two attributes will not be easy.

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14. Abstract

Mission Planning is not new in concept, and as applied to military aircraft missions, it must have been carried out from the very earliest days. Recent events have combined to increase interest in the subject, and the Air Forces of many of the NATO nations are taking steps to develop and procure mission planning systems that have capabilities far in advance of those previously available. In addition, increased interest is being shown in using airborne computer-based systems to plan and re-plan missions while they are in progress.

This report describes the Phase 2 work of the AMP/AVP Joint Working Group 15 on Mission Planning Systems and follows on from the Phase 1 report which was published as AGARD-AR-296.

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P.T.O.

AGARD-AR-313

Mission planning systems
Pre-flight mission planning
In-flight mission planning
Mission rehearsal
Automated mission planning systems
Ground-base mission planning
Airborne mission planning

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